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جامعة محمد خيضر بسكرة
كلية العلوم و التكنولوجيا
قسم الهندسة المدنية و الري
المرجع: ……..

Thèse de Doctorat LMD
Spécialité : GENIE CIVIL
Option : MATERIAUX DE CONSTRUCTION

Formulation et caractérisation de blocs légers de terre crue stabilisée

Présentée par :
LAYACHI Safa

Soutenue publiquement le :

Devant le jury composé de :

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الجمهورية الجزائرية الديمقراطية الشعبية

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وزارة التعليم العالي و البحث العلمي

Ministry of Higher Education and Scientific Research

Mohamed Khider University - Biskra

Faculty of Science and Technology

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جــامعة محمد خيـضر بســكرة

كـلية العلــوم و التكـــنولوجـيا

قسـم : الهـنـدسـة المـدنيـة و الــري

المرجع: ....

Thesis presented with a view to obtaining

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Option: CONSTRUCTION MATERIALS

Formulation and characterization of lightweight blocks of stabilized raw earth

Presented by:

Safa LAYACHI

Publicly supported on:

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DEDICATION

To my dear parents, to all my family

Safa LAYACHI

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‘ My success is only by Allah’

Abstract

The excessive consumption of energy used to ensure the indoor thermal comfort of buildings has led to a rise in the economic and environmental impacts of the construction sector. On the other hand, one of the most important challenges for future construction is reducing energy consumption, which is why the scientific community is working on developing lightweight, insulating, and environmentally friendly building materials. The main purpose of this research is to study lightweight samples (LWS) made of raw earth, stabilized with lime, mixed separately with each of these four materials: expanded polystyrene beads (ESP), and three different sizes of DPW (DPW < 1 mm, DPW (1–5) mm, and DPW (5–10) mm). In this context, the study evaluated the effects of substituting a portion of the studied soil volume with different percentages of ESP beads (0%, 40%, 45%, 50%, 55%, 60%, and 65% by volume) and different sizes and contents of DPW (0%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, and 75% by volume) on the physical, thermal, and mechanical properties of lightweight samples. The results showed that the incorporation of EPS beads and three sizes of DPW improved thermal insulation performance by an estimated 57.36%, 49.35%, 51.52%, and 54.83% for samples containing 65% EPS beads and 75% DPW < 1 mm, DPW (1–5) mm, and DPW (5–10) mm, respectively, compared to the reference samples (0% DPW). In contrast, a significant decrease in mechanical resistance was recorded compared to the reference samples. However, the values recorded for the samples were found to be usable for load-bearing and non-bearing walls. Additionally, the results of stress-strain curves revealed that the incorporation of EPS beads and DPW improved the ductility of lightweight samples.

The study also focused on evaluating the life cycle of exterior walls made by lightweight earthen samples, specifically LWSs made of 50% and 65% EPS beads, in comparison to air-blade-insulated walls. The results of the life cycle analysis of walls made of lightweight 65% EPS beads showed a reduction in required energy and a reduction of the CO2 greenhouse effect by estimated values of 19.82% and 15.86%, respectively, compared to conventional air-blade walls.

Keywords: expanded polystyrene beads (EPS beads), date palm waste (DPW), lightweight samples (LWS), lime, bulk density, mechanical performance, thermal insulating.

# الملخص

إن الاستهلاك المُفرط للطاقة المستخدمة لأجل ضمان الراحة الحرارية الداخلية للمباني يؤثر سلبا على قطاع البناء من الناحية الاقتصادية والبيئية. وعليه فإن التقليل من استهلاك هذه الطاقة يُعد أحد أهم تحديات البناء مستقبلا؛ لهذا الغرض، يعمل المجتمع العلمي على تطوير مواد بناء خفيفة الوزن ،عازلة وصديقة للبيئة.

في هذا السياق، يهدف هذا البحث أساسا إلى دراسة خواص العينات خفيفة الوزن (LWS) المصنوعة من التربة المثبتة بالجير، والممزوجة بشكل منفصل مع كل من هذه المواد: بحبات البوليسترين الموسع (ESP) أو ألياف مخلفات نخيل التمر (DPW). تم استخدام ثلاثة أحجام مختلفة من ألياف مخلفات نخيل التمر -DPW<1 mm, DPW (1-5)mm; DPW(5 (10mm. في هذه الدراسة تم تقييم تأثير تعويض جزء من حجم التربة المدروسة بنسب مختلفة من حبات ESP (0،40، 45، 50، 55، 60 و 65 ٪) و محتويات مختلفة من DPW (0،40، 45، 50، 55، 60، 65، 70 و 75 ٪) على الخواص الفيزيائية والحرارية والميكانيكية للعينات الترابية LWS. كما تم التركيز كذلك على تقييم دورة حياة الجدران الخارجية المصنوعة من الكتل الترابية خفيفة الوزن المحضرة بدمج 50% و 65% من حبات EPS ومقارنتها بنظيرتها المعزولة بفاصل هوائي. أظهرت النتائج أن تعويض التربة بحبات البوليستران EPS أو ألياف DPW يؤدى إلى تحسين أداء العزل الحراري للعينات الترابية بنسب تقدر بـ 36.57 %و35.49 %و52.51 %و83.54% للعينات التي تحتوي على 65 %من حبات EPS و75 %من 1 > DPW مم، DPW(1-5) مم، و DPW(5-10) مم على التوالي مقارنة بالعينات المرجعية. في حين أنه تم تسجيل تراجع كبير في المقاومة الميكانيكية لهذه العينات مقارنة بالعينات المرجعية. ومع ذلك، فقد وجد أن قيم المقاومة المسجلة للعينات تسمح باستخدام هذه العينات كجدران فاصلة أو حاملة. بالاضافة إلى ذلك، كشفت نتائج منحنيات الإجهاد والتشوه أن دمج حبات EPS وDPW يؤدى إلى تحسين ليونة العينات الترابية LWS. من جانب آخر، أظهرت نتائج تحليل دورة حياة الجدران أن الجدران الترابية خفيفة الوزن التي تحتوي على 65 % من حبات EPS أعطت انخفاضًا في الطاقة المطلوبة بنسبة 82.19 % و في الاحتباس الحراري لثاني أكسيد الكربون بنسبة 86.15% مقارنة بالجدران المعزولة بفاصل هوائي تقليدي.

الكلمات المفتاحية: حبات البوليسترين الموسع (حبات EPS)، مخلفات نخيل التمر (DPW)، العينات خفيفة الوزن، الجير، الكثافة الظاهرية، الأداء الميكانيكي، العزل الحراري.

Résumé

La consommation excessive d'énergie utilisée pour assurer le confort thermique intérieur des bâtiments a entraîné une augmentation des impacts économiques et environnementaux du secteur de la construction. D'un autre côté, l'un des défis les plus importants pour les constructions futures est la réduction de la consommation énergétique. C'est pourquoi la communauté scientifique travaille au développement de matériaux de construction légers, isolants et respectueux de l'environnement. L'objectif principal de cette recherche est d'étudier des éprouvettes légers (LWS) constitués de terre crue, stabilisés à la chaux, mélangés séparément avec chacun de ces quatre matériaux: des billes de polystyrène expansé (ESP) et trois tailles différentes de DPW (DPW < 1 mm, DPW (1-5) mm et DPW (5-10) mm). Dans ce contexte, l'étude a évalué les effets de la substitution d'une partie du volume de sol étudié par différents pourcentages de billes d'ESP (0, 40, 45, 50, 55, 60 et 65 % en volume) et de différentes tailles et teneurs en DPW (0 %, 40 %, 45 %, 50 %, 55 %, 60 %, 65 %, 70 % et 75 % en volume) sur les propriétés physiques, thermiques et mécaniques des éprouvettes légers. Les résultats ont montré que l'incorporation de billes de PSE et de trois tailles de DPW a amélioré les performances d'isolation thermique d'environ 57,36 %, 49,35 %, 51,52 % et 54,83 % pour les éprouvettes contenant 65 % de billes de PSE et 75 % de DPW < 1 mm, DPW (1-5) mm et DPW (5-10) mm, respectivement, par rapport aux éprouvettes de référence (0 % DPW). En revanche, une diminution significative de la résistance mécanique a été enregistrée par rapport aux éprouvettes de référence. Cependant, les valeurs enregistrées pour les éprouvettes se sont révélées utilisables pour les murs porteurs et non porteurs. De plus, les résultats des courbes contrainte-déformation ont révélé que l'incorporation de billes de PSE et de DPW améliorait la ductilité des éprouvettes légers.

L'étude s'est également concentrée sur l'évaluation du cycle de vie des murs extérieurs constitués de bloc de terre légers, en particulier de LWS composés de 50 % et 65 % de billes de PSE, par rapport aux murs isolés par l'aime d'air. Les résultats de l'analyse du cycle de vie des murs constitués de billes légères à 65 % de PSE ont montré une réduction de l'énergie nécessaire et une réduction de l'effet de serre CO2 par des valeurs estimées de 19,82 % et 15,86 %, respectivement, par rapport aux murs à l'aime d'air conventionnel.

Mots clés: billes de polystyrène expansé (billes EPS), déchets de palmier dattier (DPW), éprouvettes légers (LWS), chaux, densité apparente, performances mécaniques, isolation thermique.

Chapter 1

General introduction

1.1- Research background

Reducing the energy consumption of buildings and environmental degradation in all phases of their life, from construction to demolition, is one of the most important priorities that must be taken. According to the United Nations Environment Program, buildings consume around 40% of global energy, 25% of global water, and 40% of global resources; buildings are also responsible for approximately 1/3 of worldwide greenhouse gas emissions [7].

Buildings nowadays are the cause of many environmental issues owing to the fabrication of traditional building materials such as cement, brick, and steel, which require a considerable amount of thermal and electrical energy and pollute the air, water, and land [8]. The associated CO2 emissions from cement manufacturing have become a concern as its consumption grows [9]. In tandem with the energy challenges linked to excessive energy use for maintaining thermal comfort through heating and air conditioning, there is a growing interest among researchers to explore heat exchange between building interiors and the external environment [10]. Furthermore, in the pursuit of sustainable building, researchers concentrate on the appropriate use of materials that have good thermal insulation, are low in cost, and lower environmental degradation by using bio-sourced composite materials. Using raw earth is a good choice, especially in rural areas, to protect the environment and reduce energy consumption.

Earth is still the most often utilized building material in many countries around the world. Even now, over one-third of human beings live in earthen houses, and this percentage is higher in developing countries [11]. This is because of its low environmental impact and because it is known to be a natural moisture regulator, as well as its good thermal insulation. However, earth materials have certain limitations, such as low mechanical strength, limited water resistance, and reduced durability. To address these limitations, a range of chemical and physical stabilization techniques are implemented. Chemical methods encompass the utilization of lime or cement [12] , and at times, a combination of both [13]. It's important to note that the cement production process, which demands substantial energy input, exerts significant adverse effects on the environment. Conversely, the production of quicklime necessitates the heating of raw limestone containing calcium carbonate ($CaCO_3$) at temperatures around 900 °C. Consequently, the use of quicklime as a stabilizer offers more environmental benefits and contributes to reduced energy consumption. As indicated by Walker [14], quicklime proves particularly effective for cohesive soils, particularly in cases where clay and fine particles are prevalent. On the other hand, the physical technique involves performing a particle size correction and combining the fibers [12].

Earthen construction has been employed for centuries owing to its abundance, cost-effectiveness, and environmental sustainability. It is recognized as a good insulating material, capable of retaining heat more effectively than cement-based building materials. The incorporation of lightweight materials into earthen construction further enhances its insulative properties while preserving the advantages of earthen construction. These lightweight materials can be derived from either synthetic, or natural sources.

In Algeria, buildings account for about 42% of total energy consumption, with about 35% in the residential sector and 6% in the tertiary sector [15]. Consequently, the Algerian government adopted the Renewable Energy and Energy Efficiency Program, which was published in 2011, including an ambitious energy efficiency program, especially in the residential sector. Proposed measures to achieve energy efficiency in this sector include the introduction of thermal insulation in buildings, which will reduce energy consumption related to home heating and cooling by about 40% [15].

Enhancing the thermal insulation of building materials is one of the techniques to improve energy efficiency in buildings through the use of environmentally friendly materials with good thermal insulation and low cost. In pursuit of this objective, numerous researchers have developed new environmental materials using lightweight aggregates, both synthetic, like Expanded Polystyrene (EPS) [5, 16-19], and natural, such as Date Palm Waste (DPW).

EPS beads are considered very lightweight (with a density of less than 33 kg/m^3), synthetic aggregate with a closed-cell nature, non-absorbent, and hydrophobic [18]. It has energy absorption characteristics, high durability, and thermal and sound insulation [20]. In addition, it is a good heat insulator, commercially available worldwide, and generally utilized in packaging, food products, and thermal isolation [18, 21]. Over recent years, polystyrene beads have received great interest among researchers, as many studies have been conducted aimed at using them as a substitute for natural aggregates for the manufacture of lightweight concrete.

However, to our knowledge, lightweight earth concrete made of polystyrene beads has not been previously studied.

Efforts have also been made to use date palm waste (DPW) or date palm fiber (DPF) in the production of building and construction materials by mixing it with other compounds (cement, earth, gypsum, mortar, concrete, etc.)[22-25].

Algeria is one of the world's largest producers of date palms, with a palm grove area of more than 160,000 ha and 18.6 million date palms. Every year, around 200,000 tons of waste are generated from the production of dates [26]. In fact, they are burned in pyres to avoid gathering scorpions and snakes. However, the process of burning waste in the atmosphere will lead to the emission of some toxic fumes that pollute the environment and cause environmental problems. For this reason, recycling and reusing this waste is important to reduce environmental pollution and preserve natural resources, as well as because it has excellent thermal and sound insulation properties.

1.2- Aims of the thesis

Through previous studies, the possibility of using EPS and DPW materials as thermal insulation components in buildings has been explored. This study aims to experimentally investigate the effect of incorporating different proportions of EPS beads as well as the effect of the proportion and size of the DPW content in the composition of earthen samples on their physical, thermal, and mechanical properties. The primary objective is to develop highly insulated earth samples that have acceptable mechanical properties, aiming to create highly insulated walls for housing construction. In addition, as part of this study and for comparison with insulation materials currently used in buildings, the life cycle of walls in an office building constructed with different insulations was analyzed. This analysis determined their energy consumption and environmental impact from construction to demolition.

1.3- Plan of the thesis

The thesis is structured into five main chapters, each of which addresses a specific aspect of the research conducted to accomplish the stated aims and objectives.

- The first chapter presents a comprehensive overview of the thesis, outlining its aims and objectives. The research background, the problems being addressed, and the objectives of the work are defined.

- ❖ The second chapter provides a comprehensive overview of energy consumption and environmental concerns, particularly within the construction sector, and an overview of the development of thermal insulation materials throughout history. The chapiter studied the utilization of earth as a building material, its use techniques, and the advantages and disadvantages of earth construction. Additionally, it presents an overview of the literature, including general information on raw earth materials, clay minerals and their methods of stabilization, and plant and synthetic aggregates or fibers, as well as their properties. Furthermore, the chapter provides a summary of the physical and thermal properties and mechanical behavior of earth samples that include different plant waste and synthetic aggregates, along with different materials, including EPS beads.
- ❖ The third chapter commences with a comprehensive characterization of the materials employed in the production of earthen samples, encompassing earth, lime, expanded polystyrene, and date palm waste. Additionally, this chapter outlines the manufacturing techniques, mixing sequences, preservation techniques, and experimental tests employed in this study.
- ❖ The fourth chapter presents the analysis of the results obtained from the study. These results show the effects of incorporating expanded polystyrene beads and different sizes of date palm waste on the mechanical behavior and thermo-physical properties of earthen samples stabilized by lime. Additionally, it provides the results of the life cycle analysis of an exterior wall made of earthen samples stabilized by lime and incorporating expanded polystyrene beads.
- ❖ The fifth chapter summarizes the main findings and conclusions obtained in the current research and also presents contributions and suggestions for future studies.

Notation and Abbreviation

WL: The liquidity limit

WP: Plasticity limit

PI: Plasticity index

ρ: Bulk density

λ: Thermal condictivity

Cp: Specific heat

e: Thermal effusivity

C: Volumetric heat capacity

σ_f : Flexural strength

F: The force

σ: Compressive strength

δ: The deflection generated by the load F

I: The moment of inertia

E: Elastic modulus

EPS: Expanded polystyrene

DPW: Date palm waste

LCA: Life cycle analysis

LWS: Lightweight samples

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Chapter 2

Bibliographic review

2.1- Introduction

The significant challenges related to energy consumption and environmental issues in the field of construction underscore the need to explore alternative solutions for building homes that are low in energy and cost and ensure the necessary comfort of housing while addressing environmental concerns associated with pollution, all while keeping in mind the economic aspect that must be reasonable and affordable. Therefore, building with local materials that are less expensive and less polluting to the environment is a promising and effective solution. Earth matrix building materials are one of the most prominent solutions, especially in dry desert areas. In this context, the chapter reviews the issues of energy consumption and its impact on the environment in the construction sector, materials with less environmental impact and good thermal insulation, and the use of earth, plant, and industrial wastes as building materials, and mentions the advantages and disadvantages of using these materials in the production of low-cost housing. Additionally, the chapter provides a summary of the mechanical behavior and thermophysical properties of earthen samples incorporating various plant types and artificial aggregates, along with various materials incorporating EPS beads.

2.2- Energy consumption and environmental impact in the world

The global economy depends on growth fueled by energy, primarily fossil fuels. According to estimates by the International Energy Agency, global energy demand is expected to rise sharply by 53% over the next ten years as a result of the significant increase in industrial and urban activities in the world as well as the recent increase in population size [27]. The IEA emphasizes that the energy sector is responsible for two-thirds of global greenhouse gas emissions. Based on its latest estimates, global carbon dioxide emissions linked to energy production are expected to rise by 19% from 2011 to 2035, reaching 37.2 gigatonnes of carbon dioxide in 2035, compared to 31.3 gigatonnes in 2011[28] .This corresponds to an increase in average global temperatures of about 1.1 to 6.4°C by the end of 2100 [29]. An increase in the global average temperature of 2°C would cause irreversible impacts on the environment, a serious problem for human health, and serious damage to natural ecosystems.

The construction sector bears responsibility for energy and resource depletion as well as environmental damage. It accounts for approximately 40% of the world's total energy consumption, 25% of global water usage, and 40% of global resource utilization. A substantial portion of the energy used in buildings is dedicated to ensuring a comfortable indoor environment, including heating in winter and cooling in summer [30]. Additionally, buildings also contribute to roughly one-third of the planet's overall greenhouse gas emissions. Similar findings have been reported in studies conducted by American researchers and European government agencies. In Europe, this situation has led to the formulation of several environmental policies, with the most significant ones being the Energy Performance and Energy Efficiency Directive in Buildings. The European Commission has estimated that these measures will lead to an 8% reduction in energy demand for heating and cooling by 2020, a 12% reduction by 2030, and a 17% reduction by 2050 when compared to data from 2005 [7].

In the past, buildings were typically constructed using locally sourced materials. Nowadays, construction has become more global, and it has become common to build houses using universal materials such as concrete, brick, cement, steel, and aluminum. However, this shift has led to increased energy costs and environmental impacts, often associated with the production and transportation of these materials. Cement and concrete production result in significant emissions of greenhouse gases and exert pressure on the availability of natural resources. Cement represents 36% of the total emissions associated with construction activities and 8% of the total anthropogenic carbon dioxide emissions [31]. Worldwide, concrete production contributes approximately 4.8% of sulfur oxide emissions and 7.8% of nitrogen oxide emissions. In addition, the concrete industry was responsible for 9% of global industrial water withdrawals in 2012 [32].

2.3- Energy consumption and environmental impact in Algeria

The building sector is one of the most energy-demanding sectors, with a significant portion of its energy consumption dedicated to maintaining a comfortable indoor environment, including heating in winter and cooling in summer. This not only ensures the well-being of its occupants but also enhances their efficiency. In Algeria, the construction sector accounts for 34% of the final national energy consumption and stands as the largest consumer of electricity at the national level. Furthermore, between 2000 and 2012, the average annual household energy consumption in Algeria was approximately 54.55 GJ, as reported by the National Agency for the Promotion and Rationalization of Energy Use (APRUE). This number is expected to rise due to the growth of the construction sector and improvements in lifestyle. For instance, consider M'Sila Province, an interior province in Algeria, where electricity consumption in the construction sector witnessed a threefold increase between 2006 and 2018, marking a 200% surge [30].

Given that the building sector is a prominent consumer of conventional energy throughout its lifecycle, encompassing construction, utilization, and demolition, it significantly contributes to environmental pollution through the emission of greenhouse gases (GHG), particularly carbon dioxide [29, 33]. In fact, the construction sector alone is responsible for 31% of greenhouse gas emissions in Algeria. Furthermore, the CO2 emissions attributed to the construction sector in 2004 were estimated at 6.8 billion tons, with projections indicating a potential increase to 15.6 billion tons by 2030, as highlighted in the International Panel on Climate Change (IPCC) report [30].

2.4- Thermal insulation in the building

The building sector is a significant consumer of energy for ensuring thermal comfort. It is possible for the building industry, encompassing residential, industrial, and commercial structures, to contribute to reducing its energy consumption through effective insulation strategies. Effective insulation leads to energy conservation, resulting in reduced energy needs for cooling during the summer and heating during the winter [29]. The ripple effect of implementing this energy-efficient approach includes a decrease in the utilization of natural resources like petroleum and gas, which are commonly used for power generation, thereby slowing their depletion rate and consequently lowering greenhouse gas emissions [34]. Building insulation is a straightforward yet highly efficient method applicable across residential, commercial, and industrial sectors. Thermal insulation materials, composed of high thermal resistance materials or composites, are employed to decrease heat flow rates [35]. Energy loss primarily occurs through heat transfer across the building envelope, particularly through heating and air conditioning systems. This energy loss manifests in various areas within the building, including walls, ceilings, floors, and windows. Given that walls typically constitute the largest part of a building, the utilization of thermal insulation has a direct and significant impact on the overall heat gain or loss of the structure [36]. Walls, in particular, contribute to a substantial portion of heat loss, accounting for approximately 16% to 25% of the total. To address this issue, walls are often treated with insulation materials, either on the interior or exterior. In accordance with a study conducted by Necib et al [28]., it was found that insulating both the roof and walls with materials like cork and polystyrene, each with a thickness of 5 cm, can lead to an impressive reduction of overall heat gain by up to 59.09%. When increasing the insulation thickness to 10 cm, this reduction can reach an even more substantial 69.96% [28].

Consequently, building insulation helps to maintain indoor temperatures and prevent heat exchange with the external environment. A variety of materials, including fiberglass, mineral wool, foam, polystyrene, and others, are typically used as insulating materials. Another advantage of building insulation is cost savings. This is because insulated buildings contribute to energy balance and save a greater amount of energy through the application of insulation compared to the energy required to manufacture the insulating materials themselves. Furthermore, the use of thermal insulation contributes to fire protection, personal comfort, condensation control, and sound control [29].

2.4.1- The history of thermal insulation

In the history of thermal insulation, ancient peoples constructed temporary dwellings using materials like animal skins, fur, wool, and plant-based products such as reed, flax, or straw. However, these materials had limited lifespans. As societies became more settled and agricultural, there was a need for more durable housing materials like stone, wood, and earth. Earth-sheltered houses and cave dwellings gained popularity due to their cost-effectiveness and natural benefits, such as protection against animals and temperature regulation. Earth served as an excellent insulating blanket, with its high density resulting in slow temperature changes inside, a phenomenon known as thermal lag. This allowed earth-covered structures to stay warm in winter and cool in summer. Notably, the Neolithic village of Skara Brae in Scotland boasts some of the world's oldest earth-sheltered, green-roofed dwellings, dating back nearly 5,000 years.

Towards the end of the 19th century, construction techniques evolved rapidly with the emergence of new building materials like cast iron, glass, concrete, and steel. These materials posed challenges, primarily due to their unusual thermal expansion, which required extra thermal protection to prevent cracks and damage. Moreover, these modern constructions had lower thermal insulation capabilities compared to thick walls made of adobe or bricks, resulting in greater heat loss and increased heating demands. Rising energy consumption and the high costs of fossil fuels during economic crises drove the need to reduce heat losses from various sources, including building structures, steam engines, and heating equipment. Industrial architecture began to incorporate thermal insulation materials.

The focus of technological advancements was to enhance human comfort within buildings, emphasizing the need to retain heat. This led to the significance of thermal insulation in residential buildings, with developments in heating and ventilation equipment in the 1880s. Engineers started calculating heat loss and gain in buildings, marking the emergence of theories related to thermal insulation and building physics. Initially, people used natural materials, but as time progressed, they discovered specific artificial materials suitable for thermal insulation.[37]

Although synthetic insulating materials have improved thermal insulation in buildings, it has become clear that the amount of fossil fuels is limited and will run out within a certain period of time. Moreover, climate change and global warming, caused largely by greenhouse gas emissions, especially carbon dioxide from the use of fossil fuels, are pressing issues of the 21st century. Heating represents a large portion of the energy consumption in a typical family home. Thermal insulation helps reduce heat loss, lowering heating costs and carbon dioxide emissions. However, it is worth noting that the production of synthetic thermal insulation materials is energy-intensive and heavily reliant on fossil fuels. Consequently, there is a growing recognition that the adoption of natural thermal insulation materials is more prudent from both an energy consumption and environmental standpoint, as well as in terms of cost-effectiveness. For instance, in Germany, the production of natural thermal insulation materials has notably increased from 1% to 6% over the last two decades [37].

Table 2. 1: The evolution of thermal insulation materials throughout history [37].

Period of time	Causes of change	changes	Insulation materials
2.5 mill - 7000B	Nomadic life style	materials for clothing	animal skins, fur, wool
7000BC - 1870AD	Settled life style	Durable materials vegetable fibres	Earth, wood, bricks straw, eelgrass, reed
1870 – 1950	Industrial revolution calculations about heat loss	first natural insulating products	reed, cork, wood wool and flax plates, cellulose insulation
		development of brick-laying elements	ash-filled bricks, hollow bricks, AAC
		first products of artificial insulation materials	asbestos, rock wool, fiber-glass, foam glass, dross, expanded clay and perlite
1950 - 2000	Spread of plastics	Spread of artificial materials Apperance of plastis foams nearly disappearance of natural materials	polystyrene, polyurethane, polyester, polyethylene, phenolic, formaldehyde andmelamin foam
2000	CO_2 emission exhausting fossil fuels climate change global warming	revival of the natural materials	cellulose insulation, cork, straw bale, wood wool, sheep wool
		experiments with new materials	transparent thermal insulation, swichable thermal insulation, nanocellular insulation, vacuum insulation panels

2.4.2- Thermal insulation terminology

- **Thermal insulation :** thermal insulation is a material or a combination of materials used to reduce the transfer of heat between two different environments or surfaces. Its primary purpose is to slow down the flow of heat, whether it's to keep heat from escaping a warm space (such as a building in cold weather) or to prevent heat from entering a cooler space (such as keeping a building cool in hot weather) [35]. Thermal insulation works by minimizing the three main methods of heat transfer : conduction, convection, and radiation.
- **Thermal conductivity (λ):** Thermal conductivity is the measure of the heat flow passing through a material that is one meter thick with a temperature difference of one kelvin between the two opposite faces. It is expressed in $W.m^{-1}.K^{-1}$. Its value helps quantify the material's ability to conduct heat. The lower the thermal conductivity, the better the material insulates (as it indicates low conduction)[38].
- **Thermal resistance (R) :** Thermal resistance is used to quantify the insulating power of materials for a given thickness (e). It is expressed in $m^2.K.W^{-1}$.

$$R = \frac{e}{\lambda} \tag{2.1}$$

  A wall is more insulating as its thermal resistance increases. This measure is particularly significant in thermal insulation applications[38].
- **Thermal diffusivity :** Thermal diffusivity is a dynamic property of the material because it is involved in transfers in transient temperature regimes. It characterizes the ability of a material to transmit heat in terms of speed. It is expressed in $m^2.s^{-1}$ [38].
- **Thermal effusivity :** The effusivity of a material is its ability to exchange thermal energy with its environment.

2.5- Earth, a building material

The precise timeline of when humans began utilizing earth construction remains a subject of debate. Minke [39] suggests that this practice may have originated over 9000 years ago, based on the discovery of earth block (adobe) dwellings in Turkmenistan dating from a period between 8000 and 6000 BC. On the other hand, other authors [40]) propose that the use of earth for construction purposes originated during the El-Obeid period in Mesopotamia, around 5000 to 4000 BC. According to Berge [41], the oldest adobe blocks found in the Tigris River basin date back to 7500 BC, suggesting that earthen construction could have been employed for over 10,000 years. Notably, even the Great Wall of China, which was constructed approximately 3,000 years ago, contains extensive sections built using rammed earth techniques [42]. Additionally, the city of Shibam in Yemen, covering nearly 20,000 square meters, dates back to the 15th century.

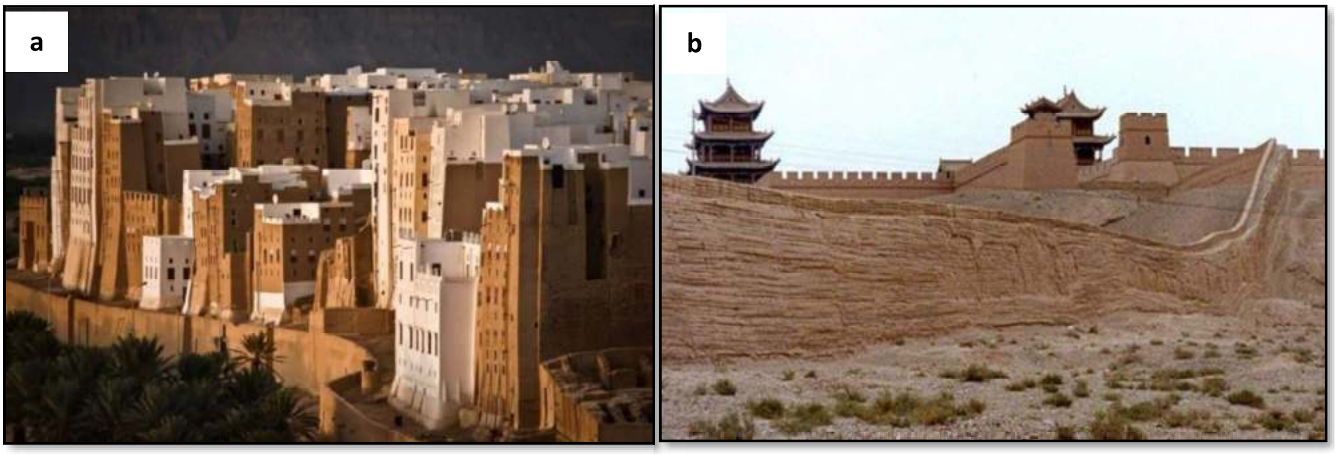


Figure 2. 1: Earthen construction in the world: (a) City of Shibam, Yemen; (b) Great Wall of China, China

Algeria is home to many earthen buildings known as kosour, which are traditional earthen buildings that have great importance as part of the country's cultural heritage. In 1943, architect Michel Loix designed a provincial hospital in Adrar, Algeria. This hospital was a leading example of an earthen public building in the area.

Earth has been a tried and tested natural building material for thousands of years, and when combined with modern methods, it can be utilized for constructing modern, environmentally friendly buildings. Currently, nearly 50% of the world's population resides in earthen dwellings While the majority of earthen constructions are found in less developed countries, this construction technique can also be observed in developed nations such as Germany, France, and even the United Kingdom, which boasts over 500,000 earthen dwellings [42]. Earth building techniques have experienced significant growth in Iran, the USA, as well as throughout Europe and the Middle East. The driving reason behind this growth is the growing interest in environmentally friendly construction [43].

2.6- Earth building techniques

On a global scale, raw soil, or earth, has been used as a building material for thousands of years and is still widely used today. It gave rise to a wide range of traditional building methods, such as wattle and daub, cob, mud brick, compressed earth block masonry, and rammed earth. It is estimated that over two billion people live in earthen structures at this time, and approximately 10% of World Heritage properties have earthen construction [44].

2.6.1- Rammed earth

Rammed earth is a technique of building mud walls that involves placing layers of moistened, well-mixed soil into formwork and compacting each layer on top of the previous one using a pestle. The wall is left to dry naturally until it reaches its full strength [45].

Figure 2. 2: a) Method of making an earthen rammed wall for a Hmong house in Vietnam ; b) The entrance edifice of the Eden Project in Cornwall, England, UK.

2.6.2- The wattle and daub

The wattle and daub technique is based on filling a supporting wooden structure (half-timbered) with earth mixed with fibers (usually straw). This technique has been in use for almost 6,000 years [42].

2.6.3- Cob

Cob is a traditional earth-building technique that has been used for thousands of years all over the world and in all climates. Where wet earth blocks are used that can be hammered with hands or feet until homogeneous walls are made. Usually, the earth is modified with fibers of different types [46].

Figure 2. 3: Cob house.

2.6.4- Adobe

is a very simple earth building technique, being the reason most of the ancient constructions were made of adobe [47]. Adobes are generally made by filling a wooden mold with damp earth and drying it in the sun. The word adobe comes from the Arabic word "Attob" which means sun-dried brick [48]. Currently, some of the processes involve adding straw for better thermal insulation.

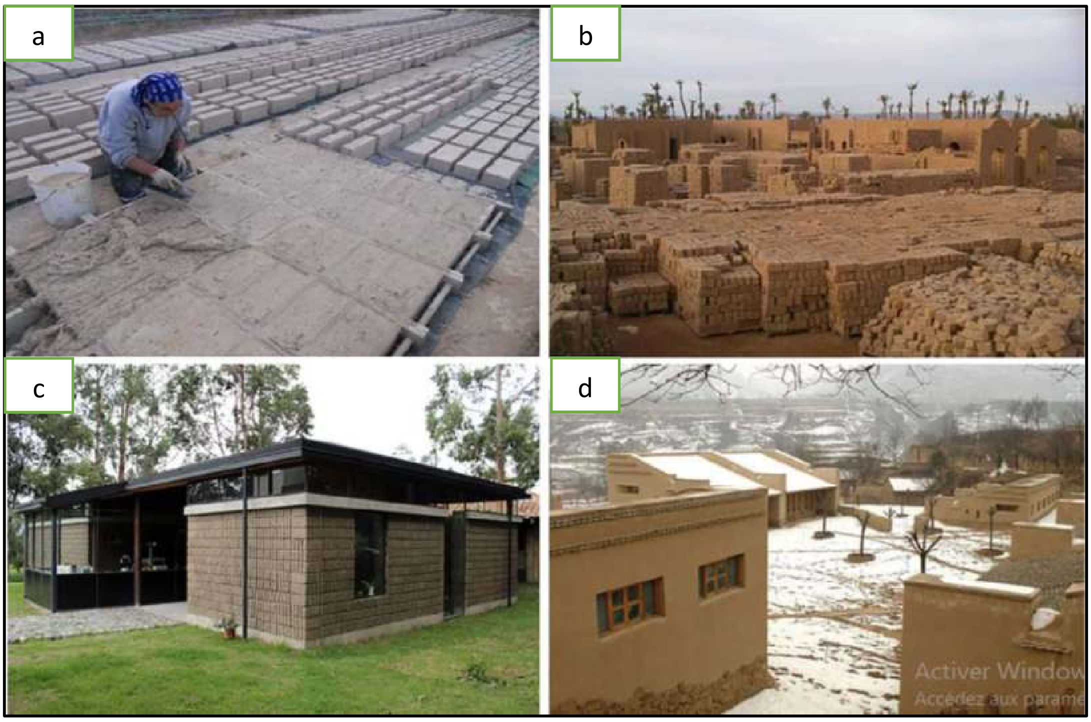


Figure 2. 4: a) Manufacture of adobe at small industrial scale in Palencia, Spain. b) Massive storage of adobes, Villa Janna, Marrakech,Morocco. C) Contemporary unplastered adobe house, Lienzo de barro, Ecuador. d) Contemporary adobe nursery school plastered with a fine soil render, Maosi, China.[49]

2.6.5- Compressed earth blocks

The use of compressed earth blocks in construction was first adopted in the middle of the 20th century. Earth-compressed bricks (ECB) are obtained by compressing earth into block molds with a manual, mechanical, or hydraulic press and are instantly loosened, unlike adobe.

Figure 2. 5: An elementary school made of compressed earth blocks in Tanouan Ibi village.

2.7- Earth as a building material (Advantages And Disadvantages)

Earth, used as a building material, is often referred to by different names, such as clay or soil. Soil is composed of a combination of clay, silt, sand, and gravel [50]. When compared to other building materials, earth has both advantages and disadvantages. Among its most important advantages, mention

- **Sustainability :** Earth is an abundant natural resource, which makes it a highly sustainable building material. It is readily available in most regions, which reduces energy use in transit and reduces environmental impact during its life cycle compared to other similar building technologies [51].
- **Thermal Performance :** Earth exhibits excellent thermal properties, offering natural insulation against both heat and cold. Numerous studies have demonstrated that earthen constructions provide superior thermal insulation when compared to concrete or brick walls [52, 53]. The effectiveness of the earth in terms of enhancing thermal comfort has been well documented in the internal environments of homes when compared to the external environment [54].
- **Sound Insulation :** Earth-based construction systems possess good acoustic properties, offering effective sound insulation. Thick earthen walls can reduce external noise, creating quieter and more comfortable indoor environments [55].

- **Cost and Energy Effectiveness :** Utilizing earth as a building material offers significant cost and energy efficiency, particularly in regions where it is abundant. Earth-based construction requires minimal processing and can be sourced locally, resulting in lower energy consumption during transportation and construction. Furthermore, it eliminates transportation costs and reduces overall construction expenses when compared to traditional modern building materials [56].
- **Environmental aspect :** The environmental aspect of raw earth construction is widely promoted as one of its significant advantages in the current context of combating global warming. The environmental impact of transportation is minimized due to the principle of using materials available near the construction site. Additionally, raw earth construction is nearly infinitely recyclable, further enhancing its sustainability [57].
- **Fire resistance :** Earth-based materials possess inherent fire-resistant properties. During the Medieval period (13th to 17th centuries), earth was widely utilized throughout Central Europe as infill in timber-framed buildings and to cover straw roofs, rendering them fire-resistant [39].

However, earth as a construction material suffers from drawbacks related to its mechanical properties, including low compressive strength and vulnerability to weathering agents, which restrict its widespread usage [58]. These limitations, coupled with the challenges of periodic maintenance of earthen structures, prompt the consideration of alternative materials such as cement, concrete, steel, and others [59].

2.8- Composition of earth

Soil is the solid component of the terrestrial sphere, covering the ground with loose materials of varying thickness, providing support for living beings and their activities, as well as serving as a medium for plant growth. It results from the transformation of the underlying substrate under the influence of various physical, chemical, and biological processes, which are linked to bioclimatic conditions as well as the presence of animal and plant life [60].

Engineering science classifies soil particles based on their diameter : those with diameters smaller than 0.002 mm are referred to as clay, while particles ranging from 0.002 to 0.06 mm are called silt, and those between 0.06 and 2 mm are categorized as sand. Larger particles are termed gravels and stones. Another type of soil is loam, which is a mixture of clay, silt, and sand and may occasionally contain larger aggregates such as gravel and stones [39].

2.8.1- Clay

To distinguish between the concepts of 'granulometric' clay and 'mineralogical' clay. In the former, the term 'clay' refers to the soil fraction with grains of a diameter < 2 µm, regardless of their chemical or mineralogical nature. In the second case, it involves mineralogical species characteristic of clays. Consequently, clays in the mineralogical sense of the term are part of the family of phyllosilicates (sheet silicates), along with micas, produced during the degradation of minerals in source rocks, particularly feldspars [61].

Clay particles differ from those of other fractions of the earth due to their chemical constitution and physical properties. Chemically, in its normal state, clay is composed of numerous associated minerals such as carbonates (dolomite, diobertite, calcite, argonite, etc.), silica (cristobalite, tridymite), aluminum oxides and hydroxides (corundum, diaspore), and even iron minerals [62]

2.8.1.1- Clay families

There are many types of clay, but the three most common clay mineral types are as follows :

- **Kaolinite**

Kaolinites are dioctahedral clays of type 1:1 (or T-O) with a sheet thickness of approximately 7.2 Å (Figure 2.6). When two kaolinite sheets are superimposed, the O- present on the upper surface and the H+ on the lower surface form a robust O-H hydrogen bond between them. This bond, combined with Van der Waals forces, imparts significant stability to a stack of vis-sheets, rendering them resistant to the effects of water. As a result, the particles exhibit stability, and their fundamental structure remains unaffected by water [62]

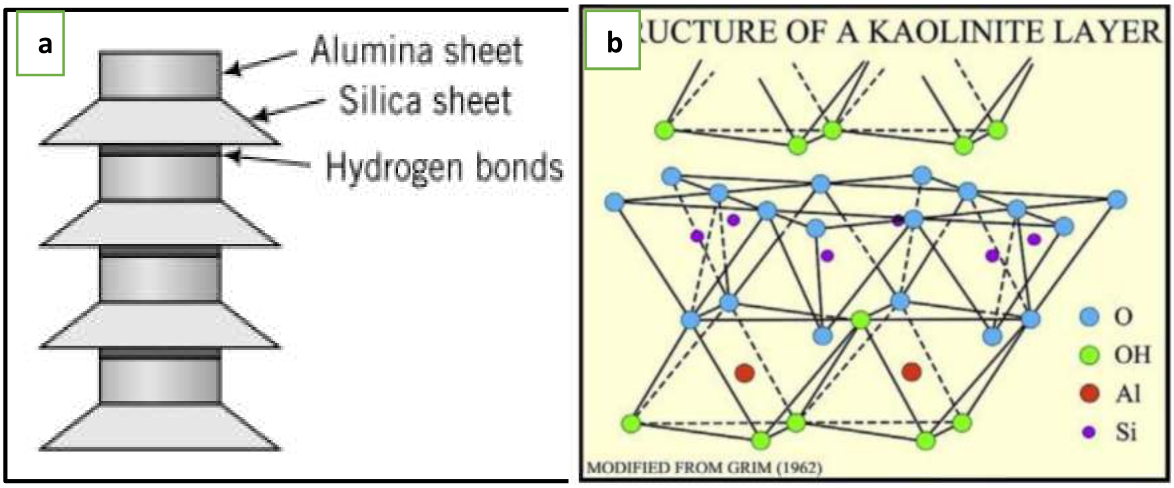


Figure 2. 6: (a) : Schematic diagram of the structure of kaolinite [1], (b): Structure of Kaolinite [6]

Montmorillonite

The elementary layer (type 2:1, or T-O-T) comprises two tetrahedral layers of silica surrounding an octahedral layer of alumina. The stacking of these layers is disordered: each layer is rotated within its plane relative to the preceding one, and it possesses a considerable lateral extension compared to its thickness, which is approximately 9.6 Å (Figure 2.7). This disorder among the layers and the composition of the lower and upper faces of these clays prevent the formation of a hydrogen bond between the layers. Consequently, this structure facilitates their separation and allows for the adsorption of various molecules (such as cations, water, and organic molecules) in the interfoliar space, causing deviation. Therefore, montmorillonite is very sensitive to water, and significant swelling of the particle can occur by the adsorption of water molecules between the layers. The thickness of the layer can vary from 9.6 Å to 15 Å or even more, depending on the nature of the compensating cation and the hydration of the interfoliar space.

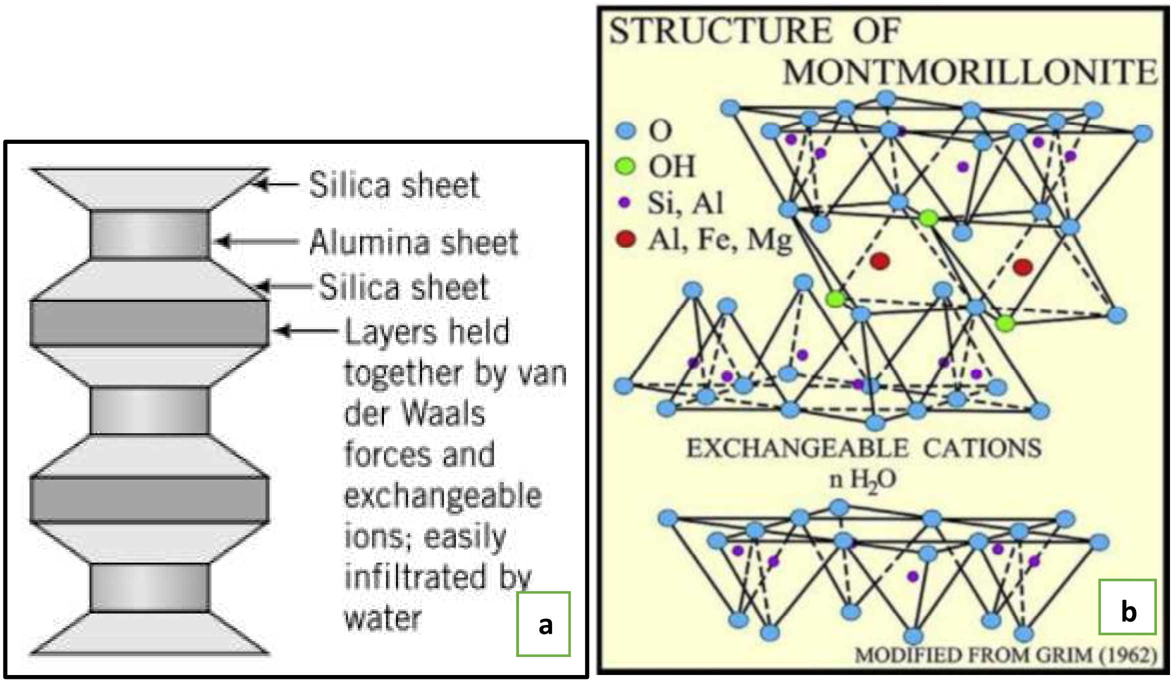


Figure 2. 7: (a) : Schematic diagram of the structure of Montmorillonite [1], (b): Structure of Montmorillonite [6]

Illite

Its structure (type 2:1) closely resembles that of montmorillonite but exhibits a higher charge deficit due to ionic substitutions by interfoliar potassium cations K+ (Figure 2.8).

Notably, K+ cations possess the unique characteristic of precisely matching the size of the surface cavities in which they are confined. The bonding of the layers by anhydrous potassium ions is robust, preventing the entry of water molecules between the layers. Consequently, these ions are non-exchangeable and non-hydratable. Illites maintain sheets with a fixed equidistance at 9.6 Å. This characteristic imparts a lower swelling potential compared to montmorillonites and contributes to the formation of larger particle sizes.

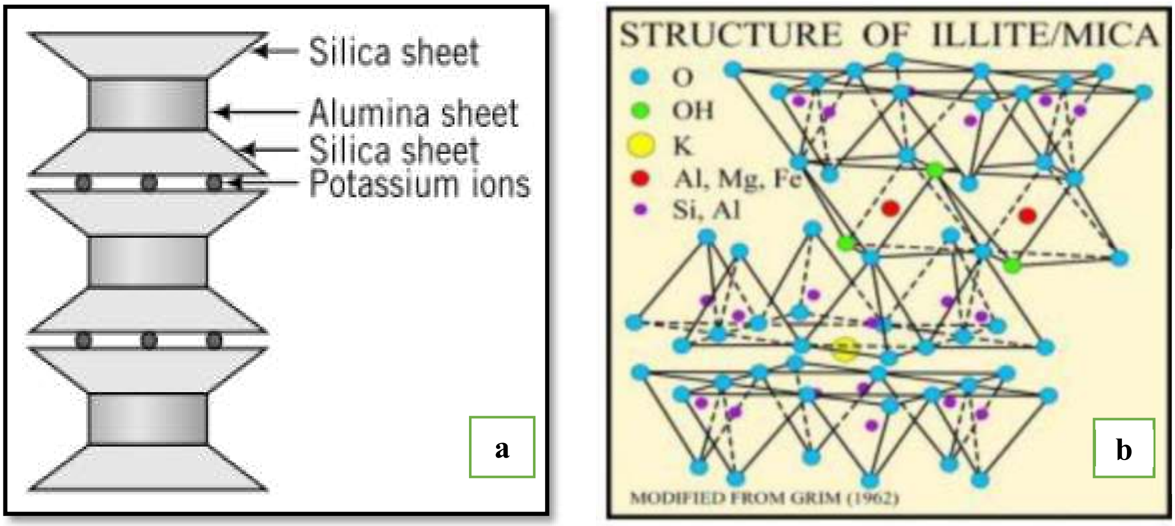


Figure 2. 8: Schematic diagram of the structure of Illite [1], (b): Structure of Illite [6]

2.9- Techniques for stabilizing earthen materials

Earth is a cost-effective, renewable natural resource and a suitable choice for making environmentally friendly building materials. However, the challenges in earth construction are ensuring its water resistance and mechanical strength. To address these issues, lime, cement, or a combination of both are offered as chemical stabilizers [14]. The stabilization process typically falls into three main categories: (1) mechanical stabilization, (2) physical stabilization, and (3) chemical stabilization.

2.9.1- Mechanical stabilization

Mechanical stabilization refers to the process of stabilizing soil through compaction. This process modifies the characteristics of the soil, including density, compressibility, permeability, and porosity, by directly impacting its structure. In their research, Guettala et al. [63] studied the influence of compaction force on the properties of CEB (Compressed Earth Block). They observed that increasing compaction stress leads to enhanced compressive strength (Figure 2.9), capillary absorption, and durability of the CEB block.

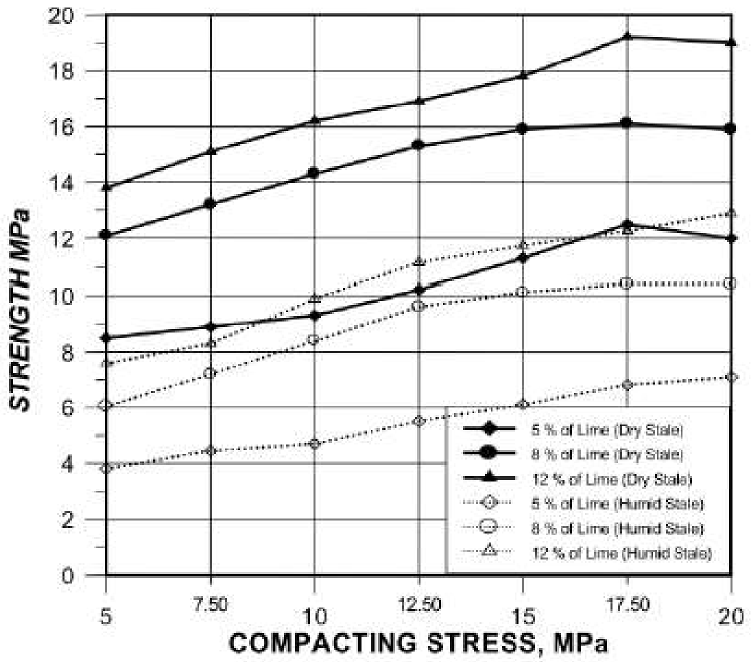


Figure 2. 9: effect of compacting stress on the compressive strength of CEB [63].

2.9.2- Physical stabilization

The characteristics of soil can be modified by changing its texture, involving a controlled mixture of various grain fractions like clay and sand. Additionally, the introduction of fibers into clay soil can prevent cracking as the clay shrinks during the drying process, enhancing the material's structural integrity. According to Guettala et al. [63], the inclusion of higher sand concentrations leads to an increase in compressive strength in both dry and wet conditions, as shown in Figure 2.10. Specifically, at a 30% sand content, there was a notable enhancement of approximately 24% in the dry state and 28% in the wet state. Similarly, Millogo et al. [64] noted that the incorporation of short kenaf fibers reduced crack propagation in earth blocks.

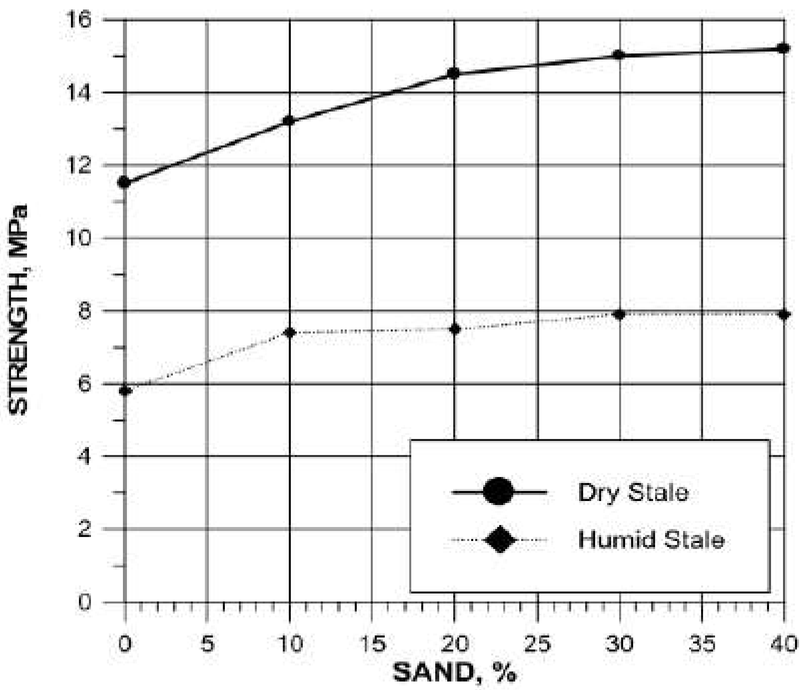


Figure 2. 10: Influences sand content on compressive strength [63].

2.9.3- Chemical stabilizers

The stabilization of soil is achieved through the introduction of additional materials or chemical products that modify its properties. This can occur either through a physicochemical reaction between the soil particles and the added substance or by creating a matrix that binds or coats the particles. Notable examples include cement, lime, bitumen, and industrial by-products. The choice and quantity of materials or chemicals to be added depend on the soil's characteristics and the desired level of enhancement, as discussed by Akpodje in 1985 [65].

2.9.3.1- Cement

Cement is considered an inorganic binder and is considered the most effective stabilizer for compressed earth blocks (CEB) [60]. It facilitates a solid connection, creating an inert bond that resists movement. Furthermore, it enhances water resistance by creating bonds among sand and gravel particles. The best results are observed in sandy soils [66]. Cement stabilization minimizes shrinkage and swelling, requiring minimal water. However, it reduces the earth's thermal conductivity. The drawbacks of cement include its high production cost and the necessity for limestone deposits. The efficiency of cement usage is influenced by the presence of iron oxides, which promote pozzolanic reactions, or a low plasticity index (<20%) in sandy soils. Conversely, the presence of organic matter, salt-laden water, sulfates, or excessively clayey soil can be detrimental to the effectiveness of cement as a stabilizer [66].

2.9.3.2- Lime

Lime Allows the formation of stable chemical bonds between clay particles. It exhibits favorable reactions with clayey soils, requiring a relatively higher water content, which depends on the quantity of lime used. Lime primarily interacts with clays and has limited interaction with sands. Lime reduces shrinkage and swelling, enhances compressive strength, and reduces water sensitivity, dry density, and plasticity [67]. Lime necessitates limestone deposits but demands less energy than cement during its production. Each soil type has an optimal lime dosage, generally ranging from 6% to 12% [66]. Clay soil, up to 70%, is favorable to lime usage. Conversely, the presence of sulfates or organic matter can be harmful [66].

During the soil stabilization process with lime, four types of reactions can occur: (1) cation exchange; (2) flocculation and particle aggregation; (3) lime carbonation; and (4) pozzolanic reactions involving lime, silica, and alumina. Reactions 1 and 2 contribute to the enhancement of soil plasticity and workability. On the other hand, reactions 3 and 4 result in the formation of cementitious products, leading to a sustained improvement in soil durability and strength for the long term [68].

- **Cation exchange and flocculation**

These reactions occur as a result of the substitution of univalent ions like sodium (Na^+) and hydrogen (H^+) within the soil with divalent calcium ions (Ca^{2+}) originating from lime. Cation exchange leads to the adsorption of calcium ions (Ca^{2+}) onto particle surfaces, reducing their electronegativity and promoting particle aggregation. The impact of calcium ions becomes noticeable immediately after lime is introduced to the soil. This leads to a reduction in soil plasticity, making it more brittle and prone to breakage. Typically, this reaction takes place within a period of 96 hours [69].

- **Pozzolanic reaction**

The introduction of lime into the soil permanently modifies its pH, even at low dosages ($pH<12$). At this pH level, SiO_2 and Al_2O_3 of the clay become soluble (Figure 2.11), and reactions as indicated in equations 2.2 and 2.3 become possible.

Pozzolanic reactions can occur slowly, lasting several months or even years. During this period, the soil's shear strength will increase while its plasticity will be reduced.

$$Ca^{2+} + OH^{-} + SiO_2 \rightarrow C\text{-}S\text{-}H \quad (2.2)$$

$$Ca^{2+} + OH^{-} + Al_2\,O_3 \rightarrow C\text{-}A\text{-}H \quad (2.3)$$

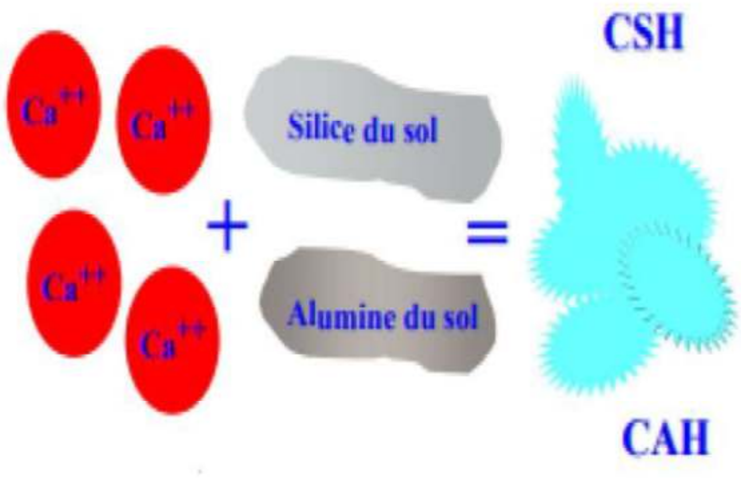


Figure 2. 11: pozzolanic reaction [70]

- **Carbonation**

Lime introduced into the soil reacts with atmospheric CO_2, leading to the formation of calcite ($CaCO_3$) (Equation 2.4). This reaction utilizes a part of the lime that is available for pozzolanic reactions [71]. Carbonation also takes place when the soil does not contain a sufficient amount of pozzolanic clay or when an excess of lime has been added.

$$CaO + CO_2 \rightarrow CaCO_3 \quad (2.4)$$

CaCO3 enhances the soil's plasticity and attaches to lime, preventing it from interacting with pozzolanic substances. As a result, incorporating excessive lime into the soil does not produce favorable results [69]

2.10- The use of natural and synthetic fibers and aggregats in earth blocks

2.10.1- Fibers

The fibers are characterized by a length that is at least three times greater than their diameter. Which constitute a variety of materials used commercially in different applications. They are classified based on their origin (natural, synthetic, and artificial), shape (straight, wavy, needle-like, etc.), size (macro or micro-fibers), and mechanical properties. However, selecting fibers for specific applications requires consideration of their compatibility with the matrix and the performance of the composite. In construction, different types of fibers are used and can be classified into three families :

- **Natural fibers**

Natural fibers can be subdivided into three large groups according to their origin, as shown in Figure 2.12

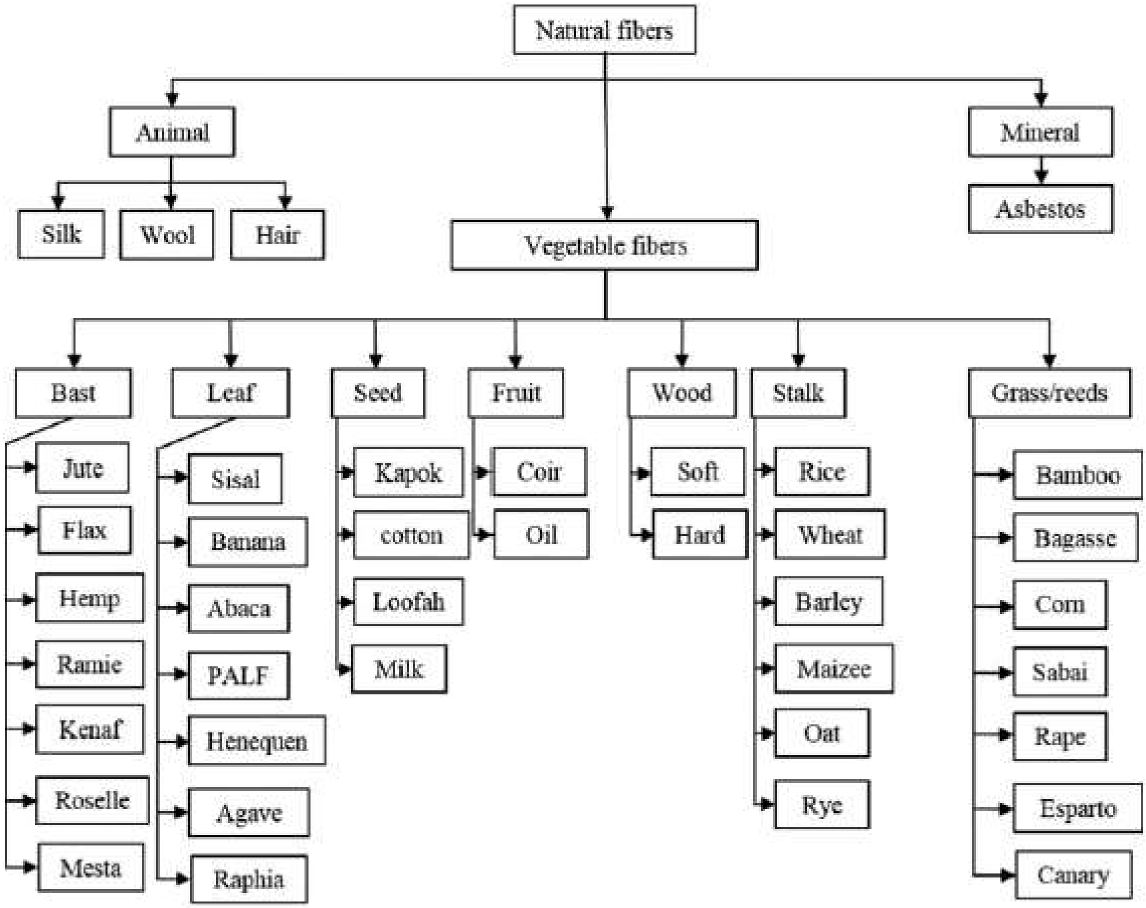


Figure 2. 12: Classification of naturel fibers [72]

- **Synthetic fibers**

Synthetic fibers, derived from synthetic polymers sourced from the petrochemical industry, emerged in the early 20th century following the success of cellulose fiber. Since then, numerous varieties tailored for specific applications have been developed through spinning. These fibers have attracted industrial interest due to their cost-effectiveness, year-round availability, and customizable properties. However, they have faced criticism for their environmental impact during production, use, and recycling. Categories of synthetic fibers on the market include polyamides (Nylons), polyesters, polyvinyl derivatives, and polyolefins like polyethylenes and polypropylenes.

- **Artificial fibers**

This type of fiber is most commonly used in the industrial field in general and in the civil engineering field in particular. It includes glass fibers, carbon fibers, steel fibers, and others. They are today the most widespread in the construction industry.

2.10.2- Aggregats

In construction, aggregates refer to granular materials used as the foundational component in various building materials. They encompass a range of materials, including :

- Natural resources like sand, gravel, and crushed stone
- Recycled materials like crushed concrete, recycled aggregate..
- Lightweight aggregate, which is divided into several types, including synthetic aggregat such as expanded clay and expanded polystyrene beads.., and natural or organic aggregate such as plant waste, is considered an environmentally friendly alternative to traditional sources.

These aggregates are blended with binders like cement or other binding agents to form diverse building materials. They vary in size and type, each serving specific purposes tailored to the requirements of construction projects.

2.10.3- Date palm

The date palm (Phoenix dactylifera L.) has been cultivated for millennia in the Middle East and North Africa region, producing approximately 2.6–2.8 million tons of waste annually, often dumped in landfills [73]. With its significant agricultural importance in Saharan regions, Algeria stands as the fourth-largest date producer globally and second in Africa after Egypt, yielding 1,904,700 tons of dates on 168,855 hectares of land in 2018 [74].

A statistical study conducted among farmers and agricultural organizations in the Biskra region estimated an annual yield of about 47.57 kg of palm residues per tree, comprising varying proportions of leaflets, rachis, petioles, fibrillium, spathes, bunches, pedicels, and thorns [75]. This versatile natural resource can be utilized similarly to other natural fibers such as jute, flax, ramie, hemp, and sisal, often employed as reinforcement in numerous industrial applications.

The use of date palm fiber and date palm bio-aggregate in construction materials and polymeric and inorganic matrices is a relatively novel application.

Each palm tree can produce around 35 kg of palm residue per year and can thrive for up to a century, resulting in an estimated annual production of approximately 4200 tons of raw palm fiber. Figure 2.14 provides a comparative analysis of the annual production of various natural fibers, demonstrating that date palm fiber production surpasses that of other sources by more than ten times, including sisal fibers [76].

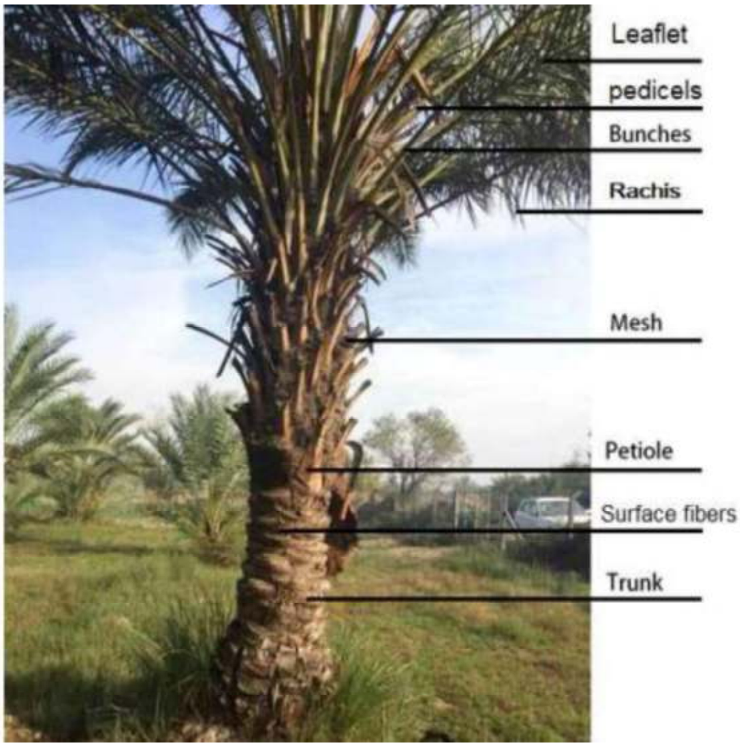


Figure 2. 13: date palm tree [77]

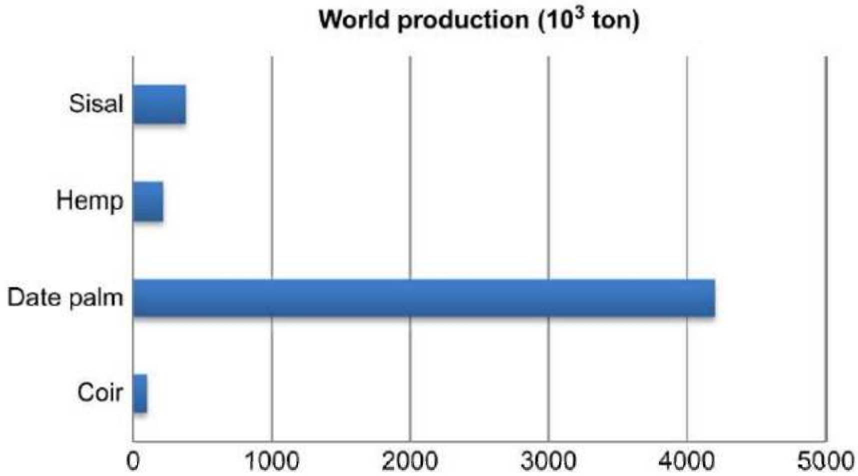


Figure 2. 14: The yearly production of certain natural fibers [76]

- **Chemical properties**

Natural fibers (NF) possess a highly intricate microstructure consisting of cellulose, hemicelluloses, and lignin within the cell wall. Cellulose, the primary component, forms a linear polysaccharide characterized by a high degree of crystallinity and regularity, thereby contributing to the strength properties of the natural fiber. Hemicelluloses, on the other hand, are composed of heteropolysaccharides, including pentoses, hexoses, and sugar acids, with a structure that is random and amorphous. Lignin, an amorphous resin derived from phenol propane, fills the gaps between the polysaccharide fibers, primarily occupying the middle lamella of NF cells and providing form and structure to the NF. These constituents vary across different NF species and significantly impact the physical, mechanical, and thermal properties of the resulting polymer composites. Vegetable fibers are categorized as natural compounds with a cellular microstructure. Each type of natural fiber possesses specific proportions of cellulose, lignin, and hemicellulose, contributing to the diverse layers. [77].

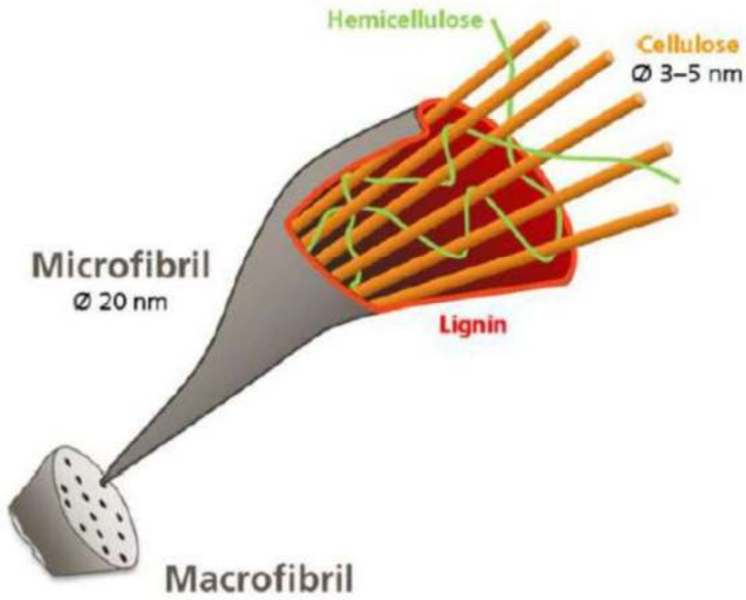


Figure 2. 15: Diagrammatic representation of the structural composition of a plant-based fiber [72]

- **Physical Properties**

Table 2.2 presents the physical characteristics of different types of date palm fibers compared with sisal and jute. Notably, surface fibers demonstrate relatively higher absolute density values (ranging from 1300 to 1450 kg/m3), similar to those of jute fibers (1300 to 1460 kg/m3), compared to the other types of fibers listed in this table. Conversely, the water absorption to saturation ratio for petiole fibers (at 146.32 ± 21)% and fibrillium (at 115.11 ± 15.7)% is higher than that of other palm fibers and various natural fibers.

Table 2. 2: Physical characteristics of date palm fiber compared with some natural fibers [77]

Fiber type	Bulk density (kg/m^3)	Absolute Density (kg/m^3)	Natural moisture content (%)	Water absorption to saturation (%)
Surface DPF	512 -1089	1300 - 1450	9.5 - 10.5	97 - 203
Petiole DPF	160 ± 54	866 ± 20.5	---	146.32 ± 21
Leaflets DPF	411 ± 41.4	830 ± 23.6	---	96.6 ± 1.4
Pedicels DPF	425 ± 23.6	749 ± 25.6	---	73.78 ± 3
Fibrillium DPF	209 ± 31.7	786 ± 23.6	---	115.11 ± 15.7
Sisal	900	---	10.4 - 13.3	110.0 - 240.0
Jute	---	1300–1460	12	---

- **Mechanical properties**

Table 2.3 summarizes the tensile strength, elongation at break values, and modulus of elasticity for each part of date palm fiber and compares it with some natural fibers. From the table values, it can be noted that date palm fibers are characterized by a slight difference in mechanical properties depending on their part. For example, the surface fibers have the maximum average tensile strength (170 MPa) and elastic modulus (4.74 GPa), while the pedicels fibers have the lowest average tensile strength (86 MPa) and elastic modulus (3.00 GPa). Petiole DPF has the lowest elongation value (0.95%), while surface DPF has the highest value (16%). This difference in properties is due to its physical and chemical properties [30] (high cellulose content).

Table 2. 3: Mechanical characteristics of date palm fiber compared with some natural fibers [77]

Fiber type	Tensile strength(MPa)	Elongation %	Modulus of elasticity (GPa)
Surface DPF	170 ± 40	16 ± 3	4.74 ± 2
Petiole DPF	90 ± 8.87	0.95 ± 0.42	7.00 ± 2.00
Leaflets DPF	100.12 ± 43.87	2.68 ± 0.49	4.00 ± 1.33
Pedicels DPF	86 ± 5.00	2.37 ± 0.15	3.00 ± 1.00
Fibrillium DPF	90 ± 30,70	4.59 ± 0.90	3.66 ± 2.33
Cotton	287 – 597	3.0 – 10.0	5.5 – 12.6
Sisal	137 – 577	---	15.2 – 34.0
Flax	345 – 1500	1.2–3.2	27.6 – 80
Jute	393 – 800	1.5 – 1.8	10 – 30

- **Thermal conductivity**

The results revealed that the thermal conductivity coefficient of date palm fiber is 0.083 (W/mK), which is lower than the thermal conductivity coefficient of hemp fiber (0.115 W/mK) and comparable to sisal (0.07 W/mK). However, the results indicated that coconut has the lowest thermal conductivity coefficient of 0.047 W/mK [76]. Table 2.4 presents a summary of these results. Given their favorable thermal properties and relatively low density, date palm fibers are emerging as a viable option for use in building material applications.

Table 2. 4: Thermal conductivity of Date palm and other fiber types [76]

Fiber type	Date palm	hemp	sisal	coconut
Thermal conductivity W/mK	0.083	0.115	0.07	0.047

2.10.4- Expanded polystyrene beads

EPS, also referred to as expanded polystyrene, is a stable polymeric foam of polystyrene with an ultra-low density. It consists of discrete air voids in a polymer matrix, as shown in Figure 2.16. The manufacturing process involves free radical polymerization, which begins by saturating the polystyrene resin in compression molding at elevated temperatures for approximately 10 minutes. Subsequently, the polystyrene sheet, with molecular weights ranging from 160,000 to 260,000, is formed and then saturated in a CO2 pressure vessel for blowing to create the cellular structure. During the blowing process, EPS beads expand to more than eight to forty times their initial volume, depending on processing conditions such as monomer conversion and molar mass distribution [78].

Expanded polystyrene (EPS) finds applications in the construction sector primarily for insulation purposes, as well as in the packaging industry. It offers several advantages, including being cost-effective, providing sound and thermal insulation, exhibiting humidity resistance, and being easily recyclable [79].

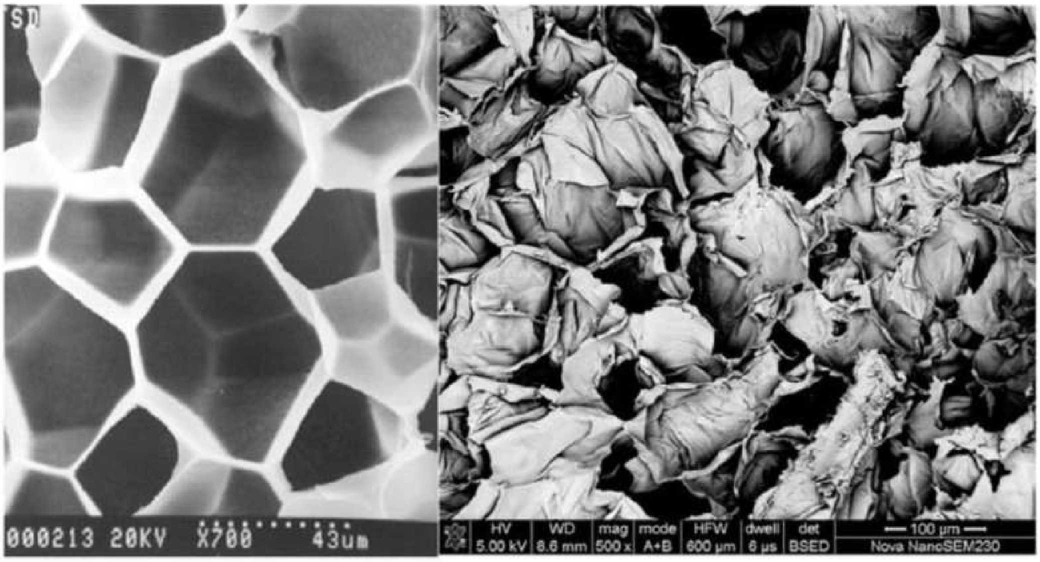


Figure 2. 16: Scanning electron microscopy (SEM) image of EPS [78]

Table 2. 5: Summary of physical and chemical properties of EPS bead [78].

Properties	Detail / Values
Polymer Polystyrene	(C6H6CH2CH2)n
Content of polystyrene	95–100%
Molecular weight	>40,000
Color	White or colored
Physical state	Cellular foam and granulated particle
Odor	Slight hydrocarbon odor
Blowing agent content (pentane)	>6% or < 1%
Nominal density	8.5–60 kg/m3
Minimum compressive stress at 10% deformation	50–165 kPa
Minimum cross-breaking strength	95–320 kPa
Softening temperature	100–120 ◦C
Melting temperature	170–200 ◦C
Ignition temperature in air	350–427 ◦C
Solubility in water	Not soluble
Solubility in other solvents	Soluble in aromatic, halogenated solvents, and ketones

2.10.4- Influence of plant and synthetic aggregats or fibers on the thermophysical and mechanical properties of unfired earth blocks

2.10.4.1- Plant aggregats or fibers

- **Bulk density**

Several authors have noted a reduction in bulk density as a result of incorporating plant fibers or aggregates into block mixtures with varying proportions and sizes [80, 81]. Literature reveals that the apparent density of these fibers and plant aggregates is generally lower or even negligible when compared to that of the soil density [82, 83].

Islam and Iwashita [84] utilized waste jute fiber at various weight percentages of 0.5%, 1%, 2%, 3%, 4%, and 5% with fiber lengths of 5mm, 10mm, 20mm, and 30mm, as well as straw fiber at different weight percentages of 0.5%, 1.5%, and 3% with fiber lengths of 10mm, 20mm, and 30mm, to manufacture low-cost earthquake-resistant adobe blocks. The results indicated that an increased fiber content in the blocks led to a slight decrease in dry density, ranging from 1110 kg/m³ to 820 kg/m³. Additionally, Vega et al. [85] investigated the effects of incorporating straw fiber into unfired earth bricks. Different percentages and lengths of straw were incorporated, namely 25% and 33.3% by volume, and lengths of 50mm and 100mm. The results indicated that as the percentage of straw fiber increased, the density decreased from 1820 to 1650 kg/m³. Khedari et al. [86] studied the effect of adding coconut coir fiber at different pourcentages (10%, 15%, and 20% of the reference cement volume) on the thermal properties of unfired soil blocks. The introduction of coconut coir into the blocks resulted in a decrease in density, reducing it from 1754.94 kg/m³ to 1344.60 kg/m³. Heath et al. [87] discovered that the inclusion of wood fiber in unfired bricks led to a decrease in dry density, reaching up to a 12% reduction (from 1793 to 1597 kg/m³) compared to the control sample. Laborel-Préneron et al. [88] incorporated 3 and 6 wt% of hemp shiv, barley straw, and corn cob in the production of unfired earth blocks, investigating both mechanical and hygrothermal properties. The results revealed a decrease in bulk density from 1878 kg/m³ to 1754 kg/m³, 1603 kg/m³ to 1221 kg/m³, and 1519 kg/m³ to 1315 kg/m³ with the inclusion of corn cob, hemp shiv, and straw fiber, respectively.

Figure 2.17 summarizes the dry bulk densities of the materials studied in the references according to their aggregate or fiber contents by weight. The values are classified according to the manufacturing technique. The clear trend of decreasing density with higher aggregate or fibrous content is clearly seen in the Figure 2.17.

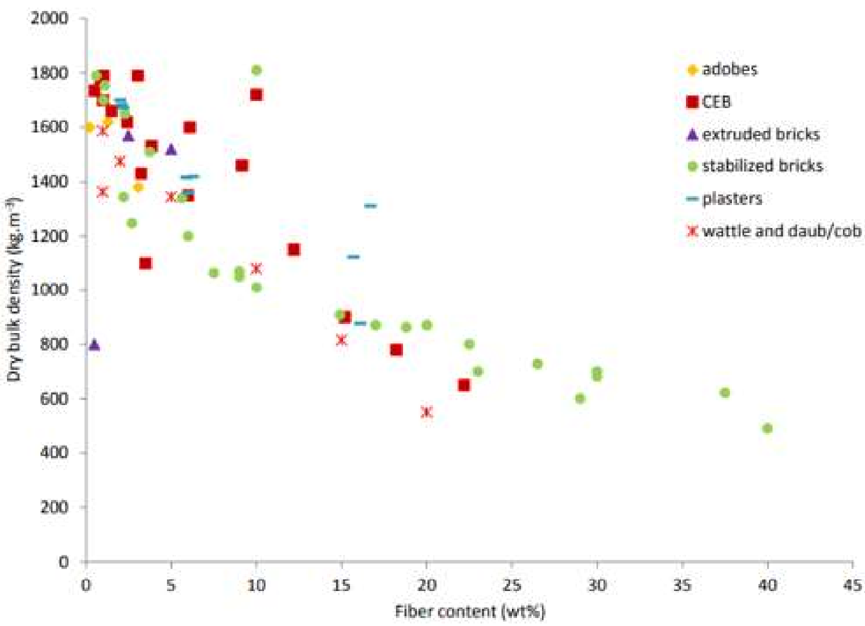


Figure 2. 17: Evaluating the dry bulk density of various manufacturing methods based on the aggregate or fiber content values provided in the literature.[11]

Mechanical properties

The effect of introducing plant particles on compressive strength varied from author to author. In some research, the addition of aggregates or fibers yielded enhancements in compressive strength under various conditions. For instance, in a study by Bouhicha et al. [89], it was demonstrated that incorporating 1.5% barley straw (the ideal reinforcement ratio) resulted in a 10% to 20% improvement in the strength of clayey soils (between 28% and 40% clay). Almeasar et al. [90] observed a 21.7% increase in dry compressive strength and a 16.5% increase in wet compressive strength when substituting 6% of date palm ash (Figure 2.18). Additionally, in the Chan investigation [91], the augmentation of pineapple and palm fibers only enhanced strength when the cement content exceeded 15% by weight.

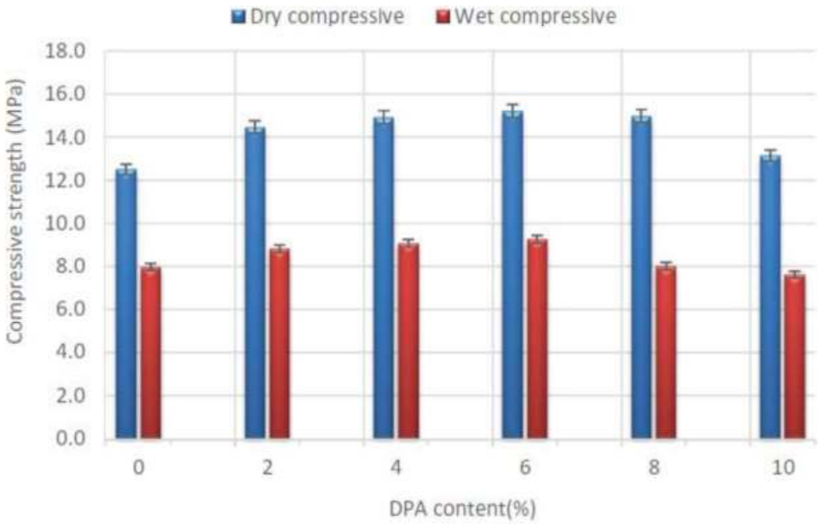


Figure 2. 18: Dry and wet compressive strength of earth mortar samples (EMS) as a function of DPA content [90]

Some studies have not reported any effect on plant aggregate or fiber additives. For instance, in the investigation by Lawrence et al. [87], the addition of wood fibers to a specific type of brick resulted in a 12% reduction in dry density but had almost no effect on the material's compressive strength. Similar results were obtained by Taallah et al. [92], who found that the introduction of fibers into compressed earth block (CEB) mixtures resulted in a slight decline in the dry strength for certain fiber concentrations, while others showed no change, as depicted in Figure 2.19.

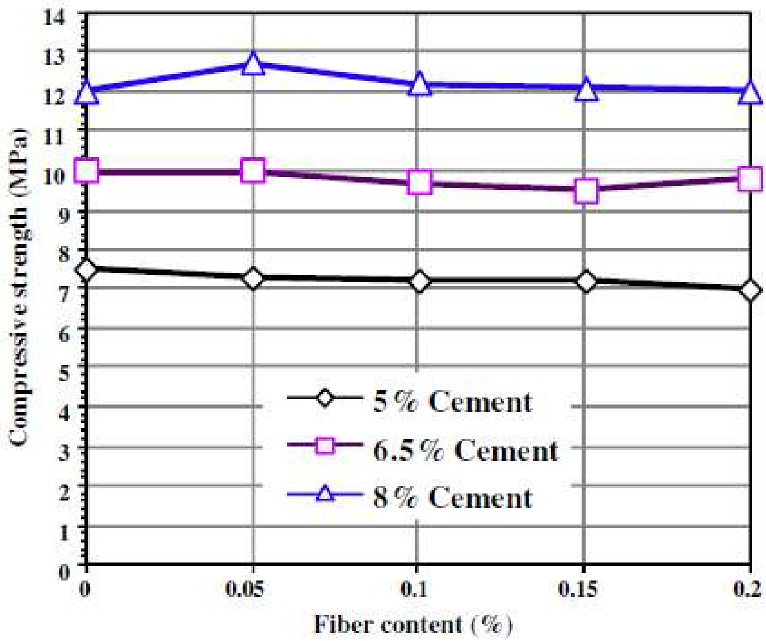


Figure 2. 19: Dry compressive strength of CEB as a function of fiber content (with 10 MPa)[92].

In other studies, the compressive strength decreased as the percentage of fibers or aggregates increased. Algin and Turgut [93], found that dry compressive strength exhibited an inverse relationship with cotton content, with a 71% decrease observed with the addition of 7% cotton. Labouta et al. [81] conducted an evaluation of how the length and proportion of Typha australis impacted both the mechanical properties and thermal conductivity of clay. Their findings revealed that with an increase in both fiber percentage and length, there was a corresponding decrease in compressive strength, as shown in Figure 2.20. Similar results were found by Millogo et al. [94], who examined the effect of fiber content and lengths on the compressive strength of compressed earth blocks filled with Hibiscus cannabinus. Their results indicated that longer fibers and high fiber contents (60 mm; 0.8 wt%) had a negative effect on the compressive strength.

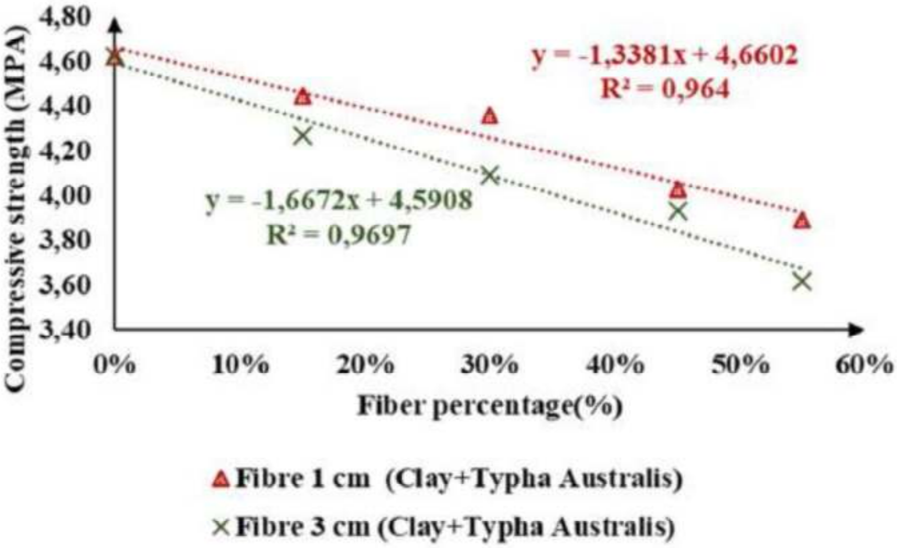


Figure 2. 20: Compressive strength as a function of fibers percentage [81]

Some research has demonstrated that incorporating plant aggregates, fibers, or sheep wool can improve flexural strength. For instance, the introduction of 25% sheep wool led to a 30% boost in flexural strength in the study conducted by Galán-Marín et al. [95]. Furthermore, Bouhicha et al. [89] conducted experiments that confirmed the beneficial effect of straw inclusion on enhancing both flexural and shear strengths, resulting in reinforced specimens with a more ductile failure mode. The same findings were obtained by Mostafa and Uddin [96], who used banana fibers with lengths varying from 50 mm to 70 mm.

In a different study, a reduction in flexural strength was observed with the incorporation of plant aggregates or fibers. For instance, Atiki et al. [97] reported a decrease in flexural strength when adding DPW, while Algin et al. [93] noted a similar decrease when incorporating cotton waste.

Mechanical behaviour

The most significant properties of building materials include their mechanical behavior and ductility. Numerous research programs have investigated the effect of incorporating plant fibers into various building materials to study their mechanical behavior. According to Laborel-Préneron et al. [80], studies on earthen bricks mixed with three types of vegetable aggregates (barley straw of different lengths (S), hemp shiv (H), and corn cob (CC)) revealed alterations in the composite's mechanical behavior. Reference specimens (FWAS) exhibit brittle failure, while specimens containing plant aggregates demonstrate high ultimate stress. Although these specimens are weaker than FWAS specimens, they also exhibit greater ductility, characterized by a larger plasticity zone (Figure 2.21). Consequently, increasing the addition of vegetable aggregates enhances the ductility of the composite.

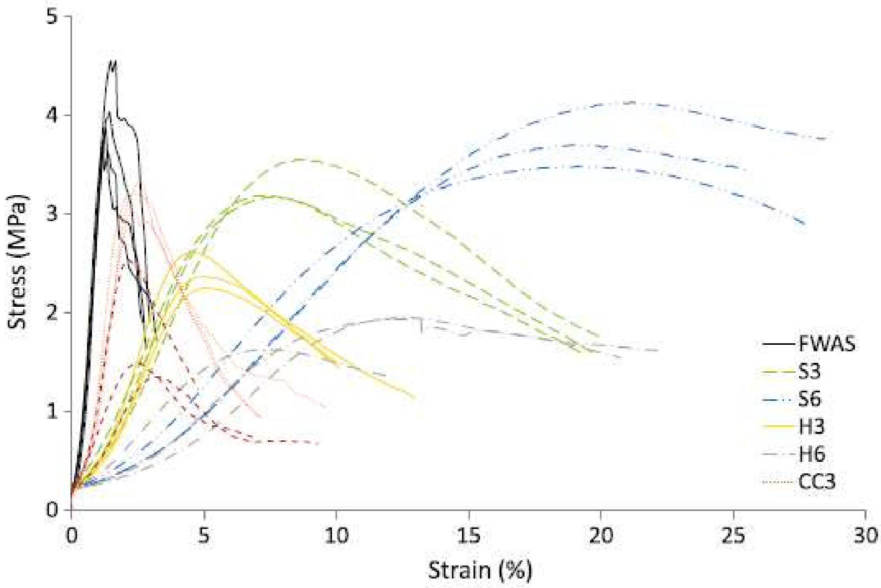


Figure 2. 21: Stress–strain curves of the compressive test for different plant aggregate contents [80]

Another study carried out by Omrani et al. [98], who demonstrated that the inclusion of Juncus fibers enables the occurrence of plastic deformation in the specimens, resulting in high ultimate stress. This is in contrast to the control sample (CCS0F), which exhibits a purely elastic phase prior to rupture localization (Figure 2.22).

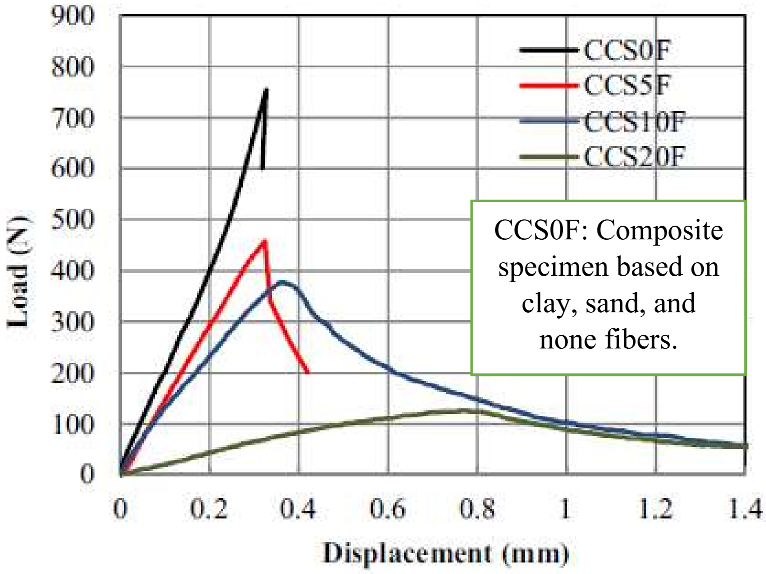


Figure 2. 22: Load-deflection diagram at different Juncus acutus fiber contents (volume%) [98]

Quagliarini et al. [99] observed a decrease in Young's modulus with increasing natural aggregate or fiber content. Young's modulus decreased from 211 MPa for earth alone to 100 to 150 MPa when up to 0.9% straw was incorporated. Additionally, Omrani et al. [98] found that adding Juncus acutus fibers to clay-sand had a negative effect on the modulus of elasticity. The modulus of elasticity of compressive and flexural decreases as the fiber percentage increases, dropping from 328.3 MPa to 35.6 MPa and 197 MPa to 21 MPa, respectively.

- **Thermal properties**

Heating and cooling energy can be conserved by employing materials with low thermal conductivity in construction [11]. Recent experimental studies have focused on evaluating the thermal insulation properties of materials mixed with plant waste, whether in the form of aggregates or fibers. These investigations [83, 94, 100-103] have repeatedly shown that increasing the proportion of aggregates or fibers results in a reduction of thermal conductivity.

The research conducted by Labouda et al. [81] indicates that increasing both the length and proportion of Typha australis fibers has a beneficial effect on the thermal conductivity of the composites, as shown in Figure 2.23. Similarly, enhancing the length of fibers demonstrated a positive impact on the thermal conductivity of compressed earth brick (CEB), as conducted by Laibi et al [104]. Additionally, when the fiber length was increased from 0.4 cm to 2.5 cm, the thermal conductivity of CEB showed a reduction from 0.63 W/m.K to 0.57 W/m.K. It's noteworthy that treated fibers displayed a higher thermal conductivity compared to their untreated fibers, as presented by Bouchefra et al [105].

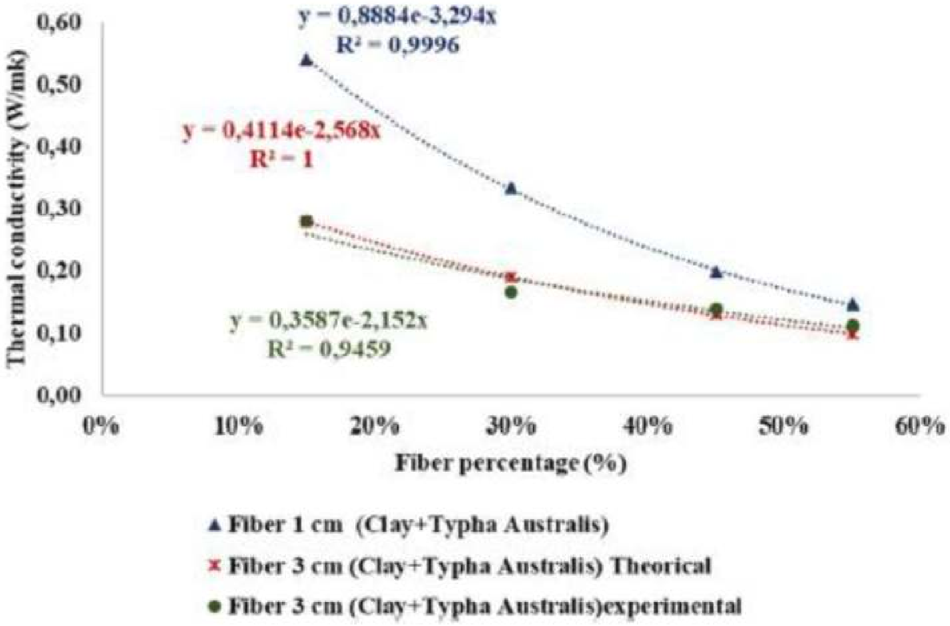


Figure 2. 23: Thermal conductivity of the composites [81]

Research conducted by Khoudja et al. [12] demonstrates a quasi-linear reduction in thermal conductivity with increasing DPW content, with an estimated reduction of 49% observed in the case of adobe bricks containing 10% DPW. These bricks exhibit a thermal conductivity of 0.342 W/mK, which is lower than that of control bricks, measuring 0.677 W/mK. Similarly, a study conducted by Liuzzi et al. [106] mixtures of clay and plaster with olive fibers revealed a decrease in thermal conductivity from 0.593 W/mK to 0.428 W/mK as the fiber content increased from 4% to 12%.

Thermal effusivity, specific heat, and volumetric heat capacity are interesting factors when evaluating the effectiveness of thermal insulation materials. In the study conducted by Djoudi et al. [107] it was discovered that as the fiber percentage increased, thermal conductivity, thermal diffusion, and effusivity decreased, while there was an observed increase in specific heat. Khoudja et al. [12] reported that as the proportion of date palm waste (DPW) in the mixture increased from 0% to 2%, the specific capacity rose from 1168.83 J/kg K to 1197.14 J/kg K, marking a 2.4% increase. Subsequently, there was a decline in the specific heat, reaching its lowest point of 1010.45 J/kg K when the DPW content reached its highest at 10%, as shown in Figure 2.24. Similar results were reported by Atiki et al. [97], who investigated the effect of incorporating a DPWA into CEB. Their findings indicate that as the content of DPWA in the CEB increased, there was a significant reduction in thermal effusivity, reaching up to a 11.63% decrease when compared with the control sample (block without DPWA).

Table 2.6 provides a summary of the physical, thermal, and mechanical characteristics gathered from existing literature for unfired earthen blocks made with plant waste.

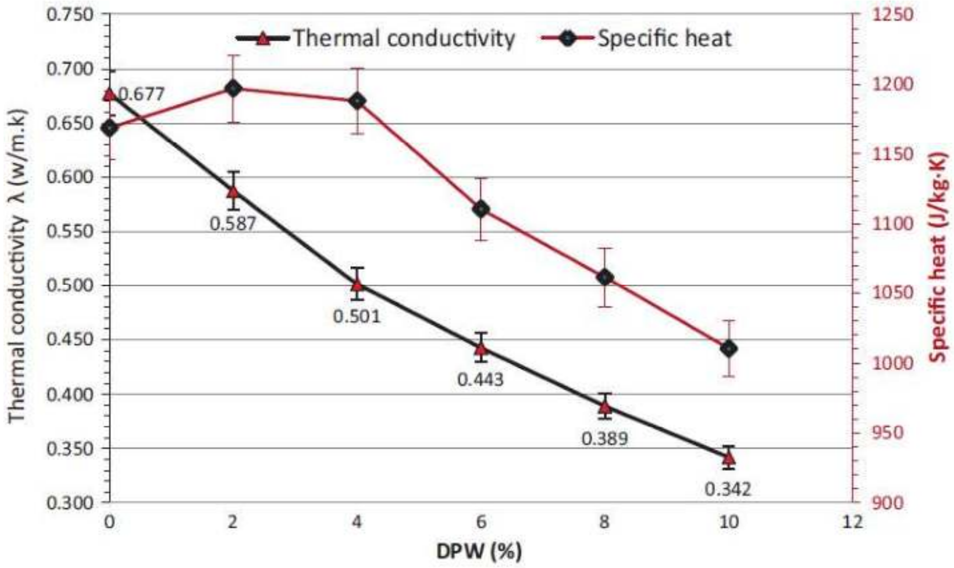


Figure 2. 24: Specific heat and Thermal conductivity as a function of DPW content [12]

Table 2. 6: Overview of research on plant waste additives for production of unfired earth blocks

plant waste	reference	Content %	Density Kg/m^3	Thermal conduvtivity W/mK	Compressive strenght MPa
Straw (Lavender (LS) , Barley (BS))	Giroudon et al [108]	3 ; 6 (by mass) 10 mm	High value = 1520 with 3% of BS less value = 1195 with 6% of BS	High value = 0.325 with 3% of LS less value = 0.155 with 6% of BS	High value = 3.9 with 6% LS less value =3.3 with 3% BS
Coconut coir (CC)	Khedari et al [86]	10 ; 15 ; 20 (by vol)	High value = 1754.94 with 10% less value = 1344.60 with 20%	High value = 0.97 with 10% CC less value = 0.65 with 20% CC	High value = 5.79 with 10% CC less value = 1.50 with 20% CC

Hemp fiber	Fernea et al [109]	50 ; 66 : 75 (by vol)	High value = 1060 with 50% less value = 966 with 75%	High value = 0.182 with 50% less value = 0.092 with 75%	High value = 0.94 with 75% less value = 0.75% with 66%
	Laborel et al [110]	3 ; 6 % 15 mm	High value= 1603 with 3% Less value= 1221 with 6%	undefined	High value= 2.40 with 3% Less value= 1.8 with 6%
Rice husk	Huynh et al [111]	10 ;20 ; 30 ; 40 ; 50	High value= 2075 with 10% Less value = 1930 with 50%	High value= 1.2 with 10% Less value = 0.68 with 50%	High value= 28.7 with 10% Less value = 14.92 with 50%
Jute	Islam et al [84]	0.5 ;1 ;2 ;3 ;4 5 ;10 ;20 ;30m m	High value= 1110 with 0.5% Less value = 820 with 4%	undefined	High value= 1.30 with 0.5% Less value = 0.68 with 4%
Date palm	Taallah et al [23]	0.05, 0.10, 0.15, 0.2 20-35 mm	High value= 1930 with 0.05% Less value = 1892 with 0.2%	High value= 0.845 with 0.05% Less value = 0.76 with 0.2%	High value= 10.2 with 0.05% DPF Less value = 9.3 with 0.2%
Sugarcane bagasse	Udawattha et al [112]	5 ; 10; 15 ; 20%	High value= 1835 with 5% Less value = 1800 with 15%	undefined	High value= 0.87 with 5% Less value = 0.54 with 20%

2.10.4.2- Synthetic aggregats or fibers

- **Bulk density**

Bulk density is one of the most significant parameters capable of influencing numerous physical characteristics. Miqueleiz [113] employed alumina filler waste (16.1%, 32.2%, and 47.82% by weight) and coal ash waste (7% by weight) as substitutes for clay in the construction of unfired bricks. Two different types of lime, namely natural hydraulic lime, calcareous hydrated lime, and Portland cement, were utilized in the experiment. The findings demonstrated a decreased sample density ranging from 1840 kg/m³ to 1500 kg/m³ with the increased inclusion of alumina fillers. Furthermore, Moussa et al. [114] explored the stabilizing impacts of 5–25% by mass of calcium carbide residue (CCR) and 8% by mass of cement on compressed earth blocks made from earth material rich in quartz-kaolinite. The findings demonstrated that incorporating CCR waste into the earth mixture led to a decrease in apparent density, reducing it from 1820 kg/m³ to 1600 kg/m³. Gandia et al. [115] conducted an experimental study on the different physical, mechanical, and thermal properties of adobe blocks incorporating glass fiber-reinforced polymer (GFRP) waste in different proportions (0; 2.5, 0.5, 7.5, and 10 wt%). The results revealed that as the percentage of GFRP waste in the adobe blocks increased, the bulk density decreased from 1619 kg/m3 to 1524 kg/m3, as depected in Figure 2.25.

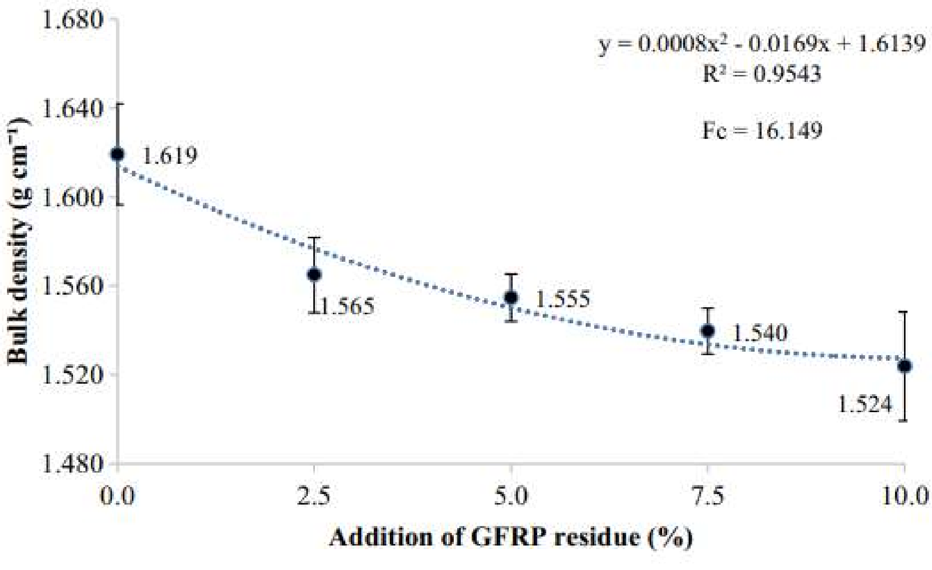


Figure 2. 25: Bulk density curve as a function of GFRP waste [115].

Mechanical properties

Zhou et al. [116] utilized Shangluo molybdenum waste as a core sample in varying proportions (55%, 60%, 65%, 70%, and 75% by weight) and cement as gelling material to manufacture unfired bricks. The resultes revealed that with an increase in molybdenum residue, the mechanical properties of unfired bricks declined. When the addition of molybdenum waste is less than 75%, the flexural strength and compressive strength are 4.83 MPa and 15.69 MPa, respectively. Another study was conducted by Porter et al. [117] , who studied the effect of adding crumb rubber to rammed earth blocks. The results show that compressive strength decreased from 10 MPa to 5.20 MPa as crumb rubber residues increased. Serrano et al. [118] examined the mechanical characteristics of adobe bricks by incorporating polyurethane (sourced from refrigerator insulation) as additives at concentrations ranging from 5% to 15% by weight. The experimental findings showed that the flexural strength and compressive strength ranged from 0.17 MPa (with 10% polyurethane) to 0.07 MPa (with 15% polyurethane) and from 2.62 MPa (with 5% polyurethane) to 1.23 MPa (with 15% polyurethane), respectively.

Thermal properties

Gandia et al. [115] found that The thermal conductivity of adobe decreased by an estimated value of 21% when the concentration of GFRP waste increased to 10%, compared with reference adobe. According to Serrano et al. [118], the addition of 20% of rubber crumbs could improve the thermal properties of adobe bricks, and the specific heat capacity value was measured at 1321 J/kgK.

According to Figure 2.26, the mixed blocks containing granulated blast furnace slag with a thermal conductivity of 0.37 W/mK [119] showed the most superior performance, followed by calcium carbide residue with a thermal conductivity of 0.47 W/mK [114], recycled aggregate (0.58 W/mK)[120], waste resulting from glass fiber reinforced polymers (0.68 W/m3)[115], and fly ash (0.78 W/m3) [121].

Table 2.7 shows a summary of the physical, thermal, and mechanical properties obtained from the literature for unfired earthen blocks containing synthetic waste.

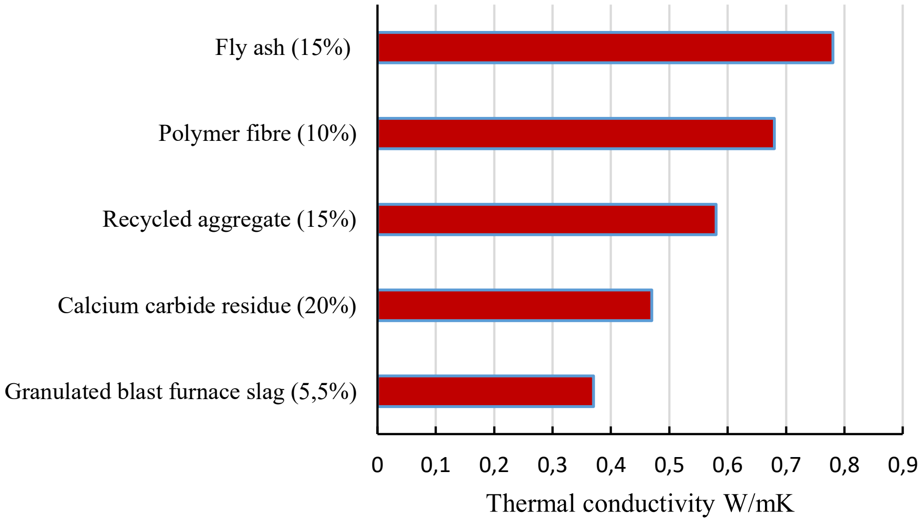


Figure 2. 26: Thermal conductivity of aggregates or synthetic fibers incorporated into unfired earth blocks

Table 2. 7: Overview of research on synthetic waste additives for production of unfired earth blocks

syntetic waste	reference	Content %	Density Max and Min Kg/m³	Thermal conductivity Max and Min W/mK	Compressive strenght (Max and Min) MPa
Fly ash (FA)	Sharma [122]	4 ; 8 ; 12	High value = 1850 with 12% FA less value = 1800 with 4% FA	undefined	High value = 2.5 with 12% FA Less value =1.4 with 4% FA
	[123]	10 ;15 ;20	undefined	undefined	High value = 6.03 with 10% FA Less value = 4.5 with 20% FA
Recycled aggregate	Bogas et al [120]	15	High value =1807 with	High value = 0.65 with	High value = 5.40 with

			CEB 8% cement less value = 1739 with unstabilized CEB	CEB 8% cement Less value = 0.58 with unstabilized CEB	CEB 8% cement Less value =2.4 with unstabilized CEB
Glass fibre reinforced polymer	Gandia et al [115]	0; 2.5 ;5 ;7.5 ;10	High value = 1619 with 0% Less value = 1524 with 10%	High value =0.86 With 0% Less value =0.68 with 10%	High value = 2.05 with 10% GFRP Less value = 1.32 with 2.5% GFRP
Ceramic waste	Ali et al [124]	50 ; 75 ; 100	High value = 1774.89 with 75% Less value =1703.33 with 100%	undefined	High value= 33.6 with 75% Less value= 15.4 with control brick
Concrete waste	Seco et al [125]	50	undefined	undefined	12.75
Plastic fibre	Binci et al [126]	2	undefined	undefined	7.10
Polystyrene fibre	Binci et al [126]	1	undefined	undefined	4.90
Calcium carbide residue	Moussa et al [114]	5 ;10 ;15 ;20 ;25	High value =1820 with 5% CCR Less value =1610 with 25% CCR	High value = 0.69 with 5% CCR Less value = 0.47 with 20% CCR	undefined

It can be observed from previous studies on the utilization of synthetic materials in unfired earth that expanded polystyrene beads (EPS) were not considered in those studies, and their physical, mechanical, and thermal properties were not investigated. Therfore, this study aims to explore the influence of incorporating (EPS) beads on the physical, mechanical, thermal properties, and life cycle analysis of raw earth stabilized with lime.

2.10.5- Influence of incorporating EPS beads on the thermophysical and mechanical properties of various materials

- **Bulk density**

Bulk density is one of the most significant parameters capable of influencing numerous physical characteristics. Nikbin et al. [20] demonstrated a significant effect of EPS quantity on concrete properties. As illustrated in Figure 2.27, the bulk density of EPS concrete varies between 2312 and 1611, notably lower than that of plain concrete. This decline is more pronounced as the amount of EPS increases. Xu et al. [127] examined the impact of varying volumes of EPS and water/cement ratios (0.45 and 0.55) on their study. The bulk density of EPS concrete ranged from approximately 1200 to 2350 kg/m³, a value lower than that of normal concrete. Similar results are shown by Ali et al. [128], who demonstrated a reduction in the average density of the control mix when the amount of EPS increased. Further, Oliveira et al. [129] utilized EPS beads in a gypsum composite to assess its mechanical properties, including density, compressive strength, flexural strength, and thermal resistance. The study revealed that the decrease in density was evident in the composite containing the highest percentage of expanded polystyrene, as depicted in Figure 2.28. For instance, when incorporating 60% EPS beads, the density decreased by as much as 55% compared to control gypsum samples without the addition of residues.

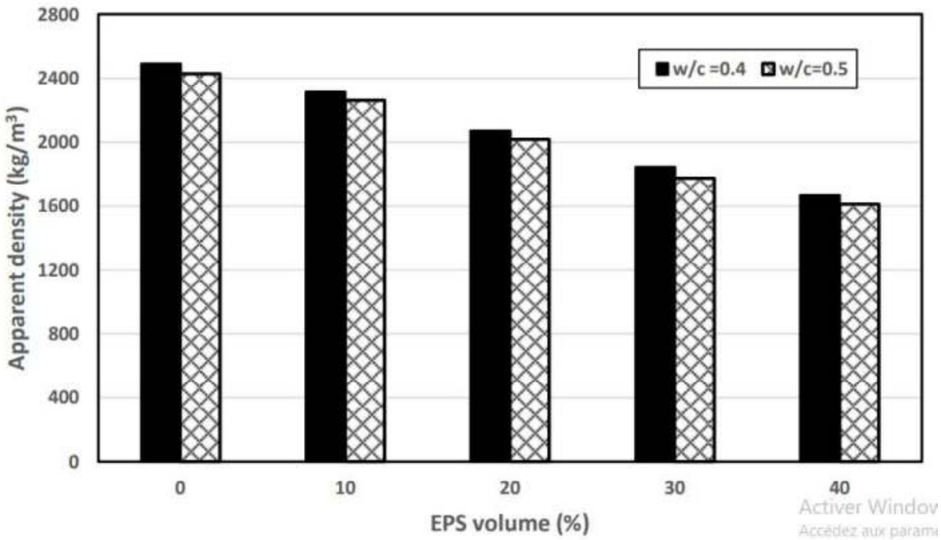


Figure 2. 27: Bulk density variation of concrete as a function of different EPS volume ratios for mixtures prepared with different w/c ratios [20]

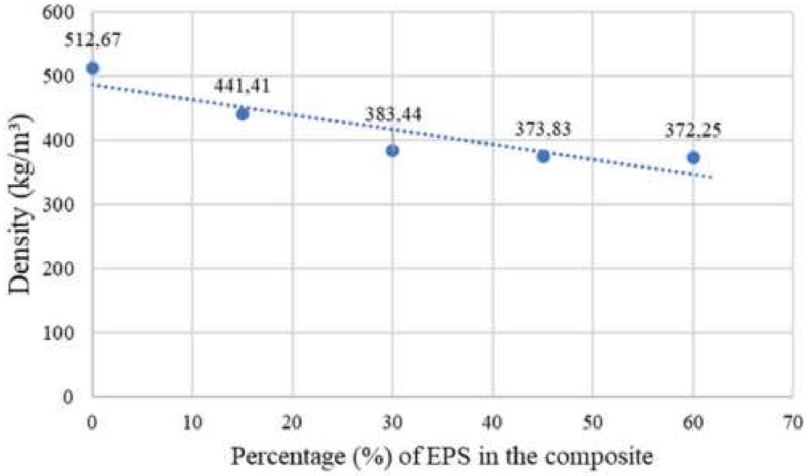


Figure 2. 28: Scatter plot of the density of lightweight recycled gypsums as a function of EPS [129]

Mechanical properties

Numerous research programs have been conducted to assess the influence of EPS on compressive strength. [18, 127, 130, 131] have all reported a decrease in compressive strength with an increase in the quantity of EPS. This reduction in strength with increasing EPS content can primarily be attributed to the considerably lower strength and stiffness of EPS aggregates when compared to natural aggregates [20]. Maaroufi et al. [16] reported that introducing 53% (by volume) of expanded polystyrene results in a notable alteration in the mechanical characteristics of the cement paste (Figure 2.29). The compressive strength decreases by 80%, aligning with findings in the literature concerning cement-based materials containing expanded polystyrene [17, 128].

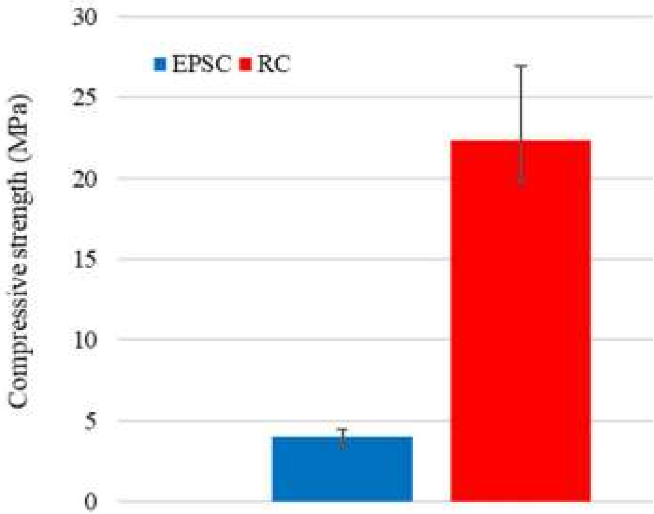


Figure 2. 29: Compressive strength of polystyrene mortar and cement paste [16]

Several research studies have focused on the decreased density of cement mixtures incorporating EPS, affecting their mechanical properties, especially strength. Table 2.8 shows a summary of various previous investigations, demonstrating that higher EPS content consistently results in reduced density and, consequently, a decrease in compressive strength.

Table 2. 8: Summary of the most important physical and mechanical properties of cement materials containing EPS beads

References	EPS content %	Density Kg/m^3	Compressive strength MPa
Ali et al [128]	(0 – 26) kg/m^3	High value =2150 control samples Less value = 995 with 26 kg/m^3	High value =8.6 control samples Less value =2.2 with 26 kg/m^3
Chung et al [132]	0 - 12.5	High value =2093 with 0% Less value =1677 with 12.5%	High value =59.1 with 0% Less value =37.25 with 12.5%
Topacio and Marcos [133]	0 - 20	High value =2420 with 0% Less value =1813 with 20%	High value =19.7 with 0% Less value = 17.7 with 20%
Sayadi et al [134]	0 - 82	High value =1200 with 0% Less value = 150 with 82%	High value =9.18 with 0% Less value = 0.93 with 82%

Flexural strength refers to the maximum stress a material can withstand before failing under a three- or four-point flexural load. Batayneh et al. [135] observed a declining trend in flexural strength as the content of plastic waste aggregate in concrete increased. However, this reduction in flexural strength was not as significant as the decrease observed in compressive strength (Figure 2.30). Ismail and Al-Hashmi investigated concrete containing 10%, 15%, and 20% plastic waste as a replacement for fine natural aggregate and found that the flexural strength tended to decrease as the proportion of plastic waste in these mixes increased [3]. Similarly, Saikia and de Brito reported lower flexural strength values for concrete containing polyethylene terephthalate (PET) aggregate compared to concrete with only natural aggregate [136].

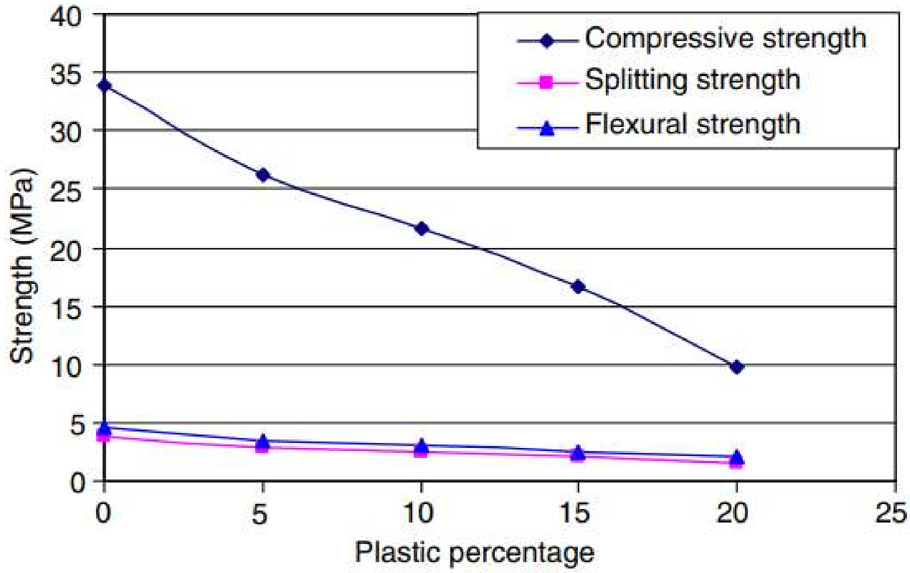


Figure 2. 30: Relationship between mechanical strength and percentage of plastic content in concrete [135]

Mechanical behavior

The stress-strain curve is a particularly important graphical representation of the mechanical properties of materials. Experimental stress-strain relationships that cover various stress regions are the most common way to represent material properties [137].

However, there has been limited research conducted on the stress-strain relationship of concrete incorporating EPS [138]. In a study conducted by Babu et al. [138], it was determined that the ultimate strain in EPS concrete is higher than that of normal-weight concrete (NWC). Moreover, as the proportion of EPS in the concrete increases, there is a decrease in the initial slope of the stress-strain relationship. According to Chen et al. [4], normal concrete usually exhibits sudden failure where the end point of the stress-strain curve is very close to the peak stress. In contrast, EPS foamed concrete exhibits a gradual failure mode, as shown in Figure 2.31. Furthermore, EPS foamed concrete has a higher ductility performance than normal-weight concrete and other lightweight concretes studied in the past. Additionally, EPS foamed concrete is able to retain the load after ultimate stress and has a high energy absorption capacity under compressive load.

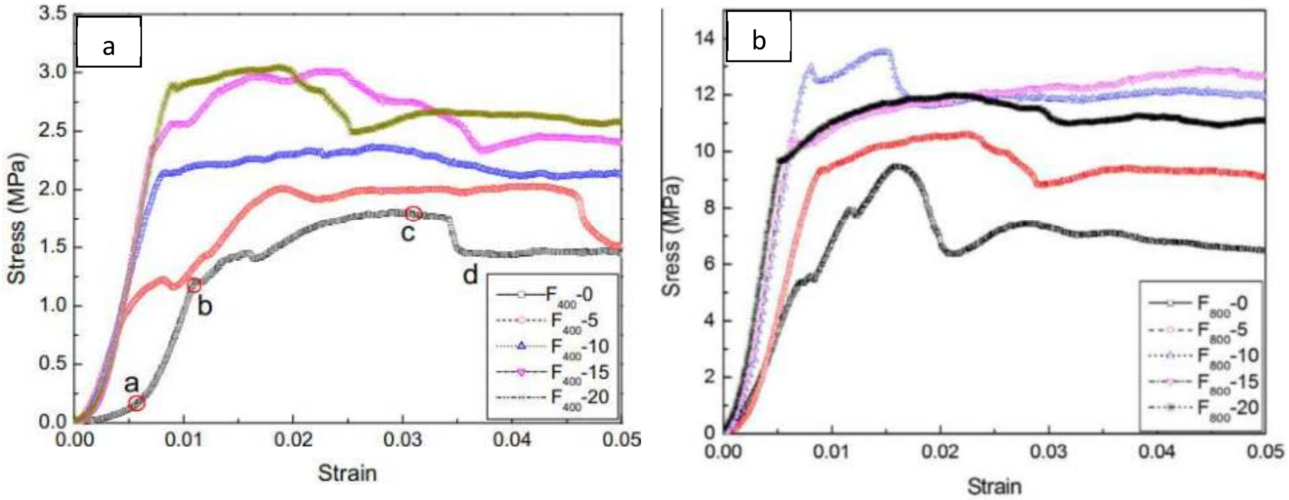


Figure 2. 31: Stress–strain curve of EPS foamed concrete with density of: (a) : 400 kg/m^3, (b) : 800 kg/m^3 [4]

According to Ismail et al. [3], reference mixtures exhibit sudden failure when subjected to centerpoint loading on simple beams, mainly due to the brittle nature of concrete, as shown in Figure 2-32a. While the samples containing 20% plastic waste showed non-brittle failure because the introduction of plastic waste particles with textured shapes into the concrete mixtures stopped the propagation of small cracks and thus prevented brittle failure of the sample during the test, as shown in Figure 2.32b.

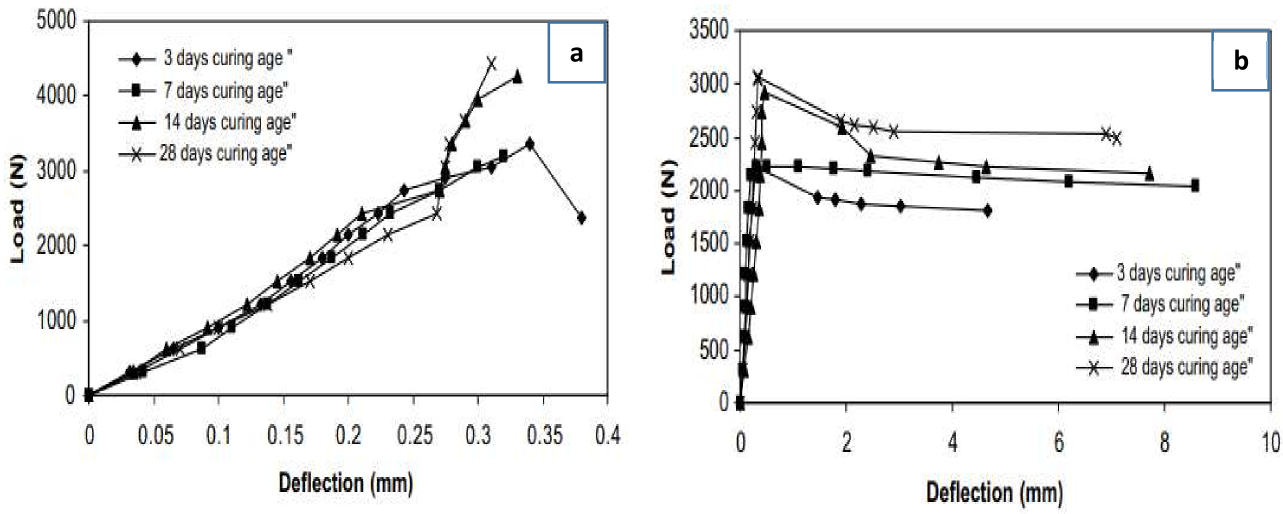


Figure 2. 32: Load–deflection curve of concrete : (a): 0% waste plastic prisms. (b): 20% waste plastic prisms [3]

Furthermore, a decrease in Young's modulus has been reported in several studies, depending on the content of expanded polystyrene. It is noteworthy that the recorded decrease in Young's modulus values ranged from the highest value, estimated at 15.5 GPa in a sample without polystyrene, to 2.3 GPa when the polystyrene content reached 26 kg/m3, as reported by Ali et al [128]. The same trends were almost recorded by Hannawi et al. [139], who noted that as the plastic content in concrete increased, the resulting elastic modulus decreased, likely because plastics have inherently low elastic modulus values and there is a weak bond between the matrix and plastic aggregates.

Thermal properties

EPS concrete offers significant advantages in civil engineering applications. These advantages include not only their lightweight properties, which can decrease structural dead loads when incorporated into designs, but also their considerable potential for enhancing thermal and acoustic insulation. This is especially important in the context of the building and construction industries, which account for a substantial portion of global energy consumption (approximately 55% of total electricity usage in 2020, as reported by Programme, 2020). Utilizing EPS concrete can contribute to reducing energy consumption in these sectors [78].

Numerous investigations have undertaken the development of mix designs for EPS concrete to achieve optimal thermal insulation properties. An overview of previous research on thermal performance characteristics consistently demonstrates an enhancement in the thermal properties of EPS concrete when the content of EPS beads increases, regardless of the change in water and humidity values between 0.45 and 0.55. Demirboga et al. [140] noted that increasing the content of EPS beads in concrete can lead to a significant reduction in thermal conductivity values, with reductions of up to 70% reported. Dixit et al. [5] conducted a study on lightweight structural cementitious composites incorporating expanded polystyrene (EPS) to improve thermal insulation. The study revealed that as the EPS content increased, there was a decrease in thermal conductivity, as depicted in Figure 2.33. From the content of 0% to 45% EPS, the thermal conductivity decreased significantly from 2.14 W/mK to 0.49 W/mK, representing a substantial 77% reduction in thermal conductivity.

Generally, the utilization of EPS concrete in thermal insulation systems is most effective when employing concrete with very low densities. Lower density results in increased porosity, and larger air gaps contribute to improved insulation performance. Table 2.9 provides a summary of the physical and thermal properties obtained from the literature for cementitious materials containing EPS beads.

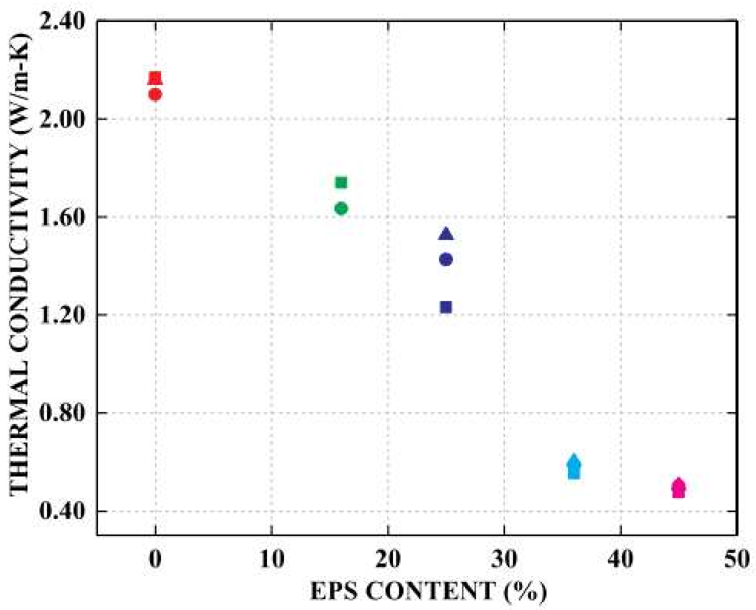


Figure 2. 33: variation of thermal conductivity of cement composites with EPS as a function of EPS content [5]

Table 2. 9: Summary of the most important physical and thermal properties of cement materials containing EPS beads.

References	Type of mixture	EPS % by volume	Density Kg/m^3	Thermal conductivity (W/(m·K))
Chen and Lui [4]	Concrete	58.5	410	0.15
		63.5	406	0.13
		68.5	405	0.10
		73.5	403	0.09
		78.5	395	0.07
Schackow et al [141]	Concrete	55	1140	0.56
		65	1070	0.50
Sayadi et al [134]	Concrete	0	1200	Na
		45	400	0.1566
		67	250	0.0927
		73	200	0.0864

		82	150	0.0848
Oliveira et al [129]	Mortar (gypsum)	0 15 30 45 60	512.67 441.41 383.44 373.83 372.25	0.7203 0.32 0.30 0.22 0.19
Selvaratnam et al [142]	Mortar	0 90 125 200	2075 1453 1282 968	0.692 0.361 0.281 0.216

2.10.6- Life cycle analysis of some thermal insulation materials

Over the past few years, concerns about the environment have significantly increased the demand for sustainable construction and developments. For this reason, the construction industry requires correct information about the environmental impact of the building materials and products used. The most appropriate method for obtaining this information was identified as a life cycle assessment (LCA) approach. LCA assesses the environmental impacts of entire processes, from production to recycling (cradle to grave) [79].

Energy sustainability and building efficiency are of great importance to cities. For this reason, insulation systems are used in buildings. Laborel-Breneron et al. [11] indicate that employing materials with low thermal conductivity (TC) can effectively reduce energy requirements for heating and cooling in buildings.

In this context, many recent studies have proposed new effective, environmentally friendly thermal insulation materials. Aramburu et al. [143] compared sustainable materials to other traditional building materials, such as expanded polystyrene , extruded polystyrene, or polyurethane foam. They concluded that the impacts resulting from the manufacture of plant fiber samples are much lower than those produced from other insulating materials as shown in Figure 2.34.

According to Cornaro et al. [144], a life cycle assessment study of straw walls (SW) and traditional walls (TW) showed that for the production and construction phases, the embodied energy (EE) in SW is about half the value related to TW, while the equivalent CO_2 emissions differ by more than 40%, as shown in Figure 2.35.

In another study by Çamur et al. [79], the environmental impacts of modern insulating materials, such as EPS and stone wool, were evaluated. The study discovered that EPS exhibits lower environmental impacts for all categories compared to stone wool, with the majority of impacts observed during the production stage.

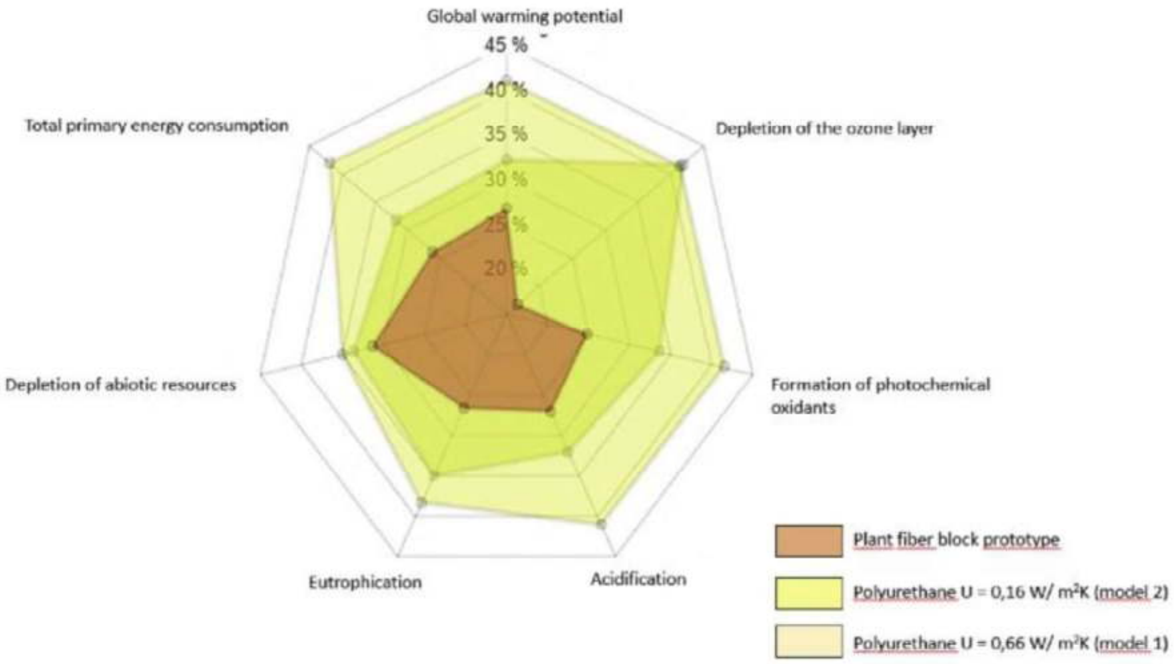
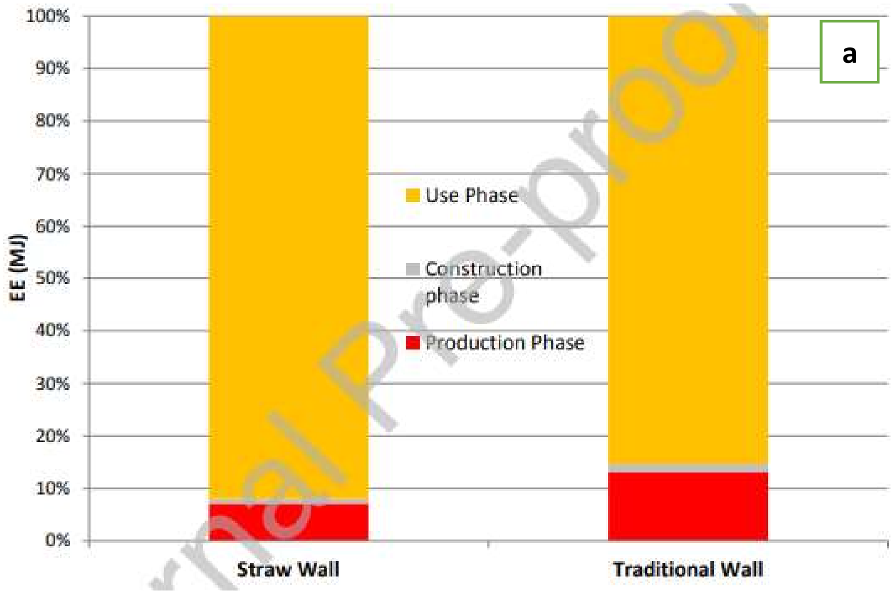


Figure 2. 34: Radar diagram of plant fiber and two models of polyurethane [143]



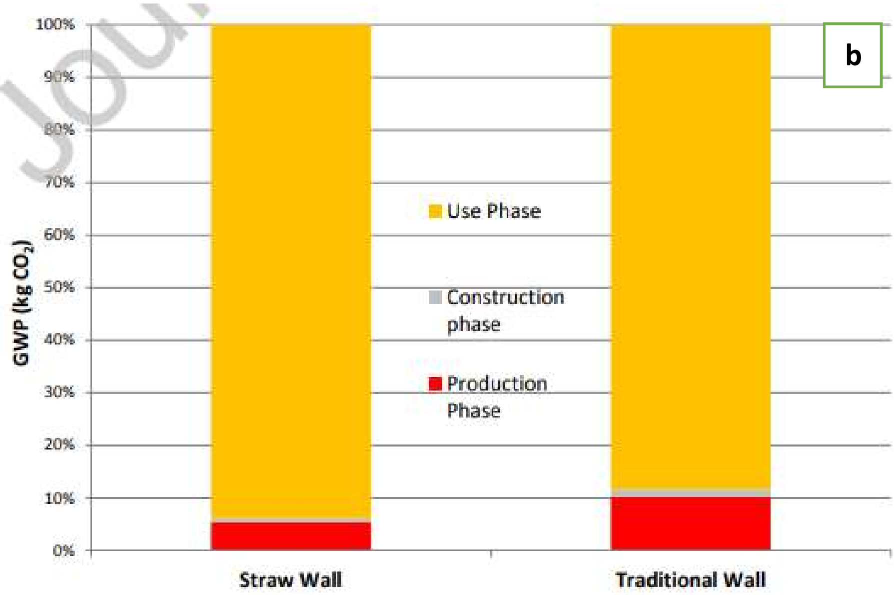


Figure 2. 35: The contributions of the different phases for the SW (straw wall) and the traditional wall TW buildings in terms of (a) EE and (b) GWP [144].

Conclusion

This chapter highlighted the general context of earth use in construction as well as different building techniques, then focused on the composition of earth and the chemical processes resulting from adding lime to soils. Furthermore, it reviews the utilization of plant and synthetic fibers and aggregates as reinforcement or filler materials in earth-based construction. Previous studies have analyzed the impact of these plant fibers or aggregates on the thermal, physical, and mechanical properties of raw earth.

To the best of our knowledge, there has been no study related to the use of polystyrene beads in soil matrix before. In addition, most of the previous research related to the use of date palm waste in soil was based on maintaining minimum mechanical resistance thresholds.

The interest of this study is to develop highly insulated earth samples that have acceptable mechanical properties, aiming to create highly insulated walls for housing construction. This will be achieved by incorporating different proportions of polystyrene beads, along with different proportions and sizes of date palm waste (great potential in the Biskra region of Algeria), to evaluate their effect on the thermophysical properties and mechanical behavior of lightweight earthen samples stabilized by lime.

Chapter 3

MATERIALS AND EXPERIMENTAL METHODS

Chapter 3

Materials and experimental methods

3.1- Introduction

The aim of this chapter is to characterize the basic ingredients for the manufacture of earthen samples and to determine the physical, chemical, mechanical, and mineral properties of soil, fibers of date palm waste, and expanded polystyrene beads. This chapter also explains the different formulations, sample manufacturing conditions, and experimental procedures. In addition, this chapter also describes the materials and the test methods that will be applied to study the samples.

3.2- Materials

3.2.1- Soil

The soil used in this work was sourced from Biskra region, located in southeast Algeria. This soil was sieved by a 2 mm sieve as illustrated in Figure 3.1. Table 3.1 and Figure 3.3 show the soil's characteristics, including its grain size and sedimentometry, were determined using the standards NF P 18–560 and NF P 94–057 successively. As well as apparent and absolute density. Atterberg limits and the soil's plasticity index were also calculated according to the standard NFP 94–051. The mineral composition of this soil was investigated using the X-ray diffraction (XRD) technique. The chemical composition of the raw soil was also determined using the X-ray fluorescence (XRF) method. The results obtained are summarized in Table 3.2, Table 3.3, and Table 3.4 successively.

Figure 3. 1 : Materials used in this study

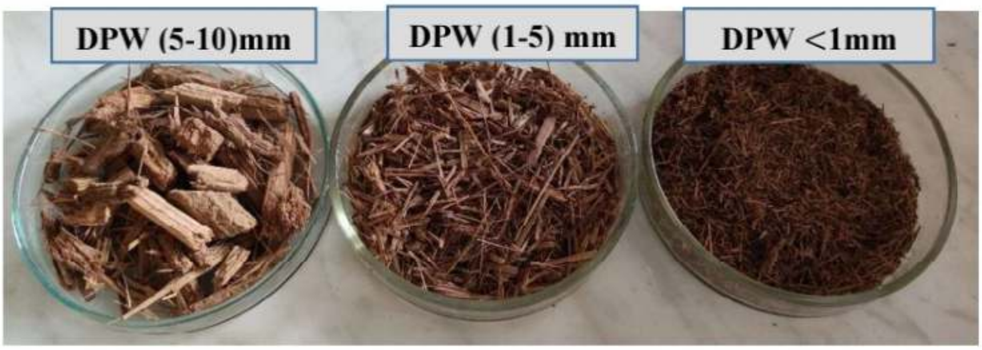


Figure 3. 2: DPW used in this study

Table 3. 1: Physical characteristics of the soil.

Atterberg limits			Apparent density (kg/m3)	Absolute density (kg/m3)	BMV
WL	WP	IP	1341	2133	5.33
32.78	19.96	12.82			

Table 3. 2: Mineralogical analyses of soil

minerals	Quartz	Calcite	Dolomite	Illite
Mineralogical composition (%)	45	42	7	6

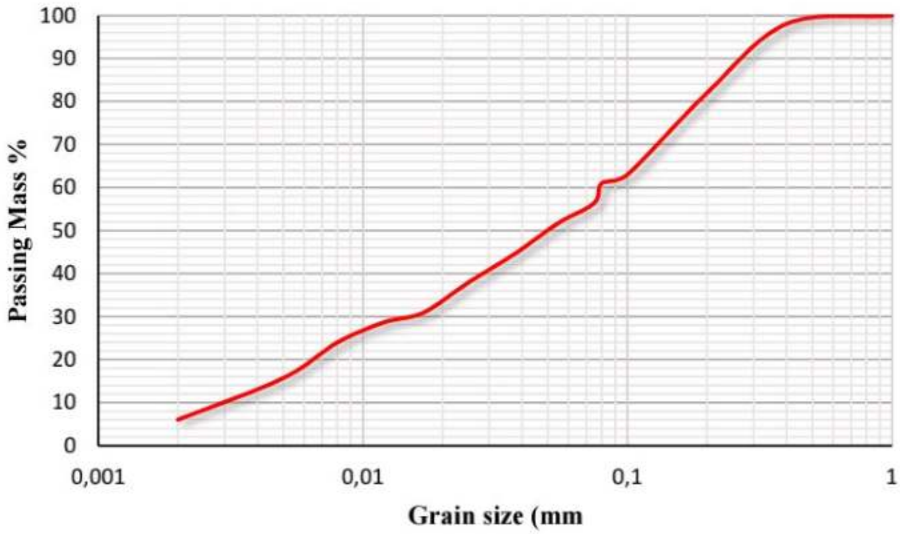


Figure 3. 3: Grain size distribution.

Table 3. 3: Chemical composition of soil

components	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	P_2O_S	T_iO_2	LOI
soil	36.065	4.86	2.3	27.62	1.975	0.26	0.8	0.2	0.115	0.31	25.505

3.2.2- Lime

The binder used in this work is quicklime, manufactured by Saida's lime unit (Algeria). The physical and chemical properties of this quicklime are illustrated in Table 3.4, and Table 3.5. [23]

Table 3. 4: Chemical composition of lime.

components	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	$CaCO_3$	CO_2
Lime	< 2.5	< 1.5	< 2	< 83.3	< 0.5	< 0.5	$0.4 - 0.5$	< 10	< 5

Table 3. 5: Physical properties of quicklime according to the technical sheet of this quicklime.

Physical properties	
Physical appearance	Dry white powder
Specific gravity	2
Over 90 μm (%)	< 10
Over 630 μm (%)	0
Insoluble material (%)	< 1
Bulk density (g/l)	600-900

3.2.3- Expanded polystyrene beads (EPS)

Expanded polystyrene beads used in this research were manufactured at the ENL factory located in the industrial zone of Oued-Smar, Algeria. Styrene, which serves as the starting material for polystyrene production, is polymerized. The EPS beads utilized in this work have a diameter of 3-5 mm and a density of 11.4 kg/m^3. The properties of EPS beads are shown in Table 3.6.

Table 3. 6: The properties of EPS beads

Properties	**Value**
Particles' size (mm)	3-5
Dry thermal conductivity (W/m.K)	0.05
Apparent density (kg/m³)	11.4

3.2.4- Date palm waste (DPW)

In this study, date palm waste (DPW) was used as aggregates and was provided by the Technical Institute for the Development of Saharan Agriculture based in Biskra, Algeria. First, palm waste (DPW) is derived from palm grove maintenance operations and used as aggregate (only aggregate from dry leaves and petiole (see Figure 3.4) crushing was used). It should be noted that these palms are renewable parts of palm trees that grow from year to year. Then they were sieved using three sizes as follows : DPW <1 mm, DPW(1–5) mm, and DPW(5-10)mm (Figure 3.2). Then it was washed with water to remove dust and impurities, then dried in an oven at a temperature of 60 °C for 12 hours. The mechanical properties of DPW (leaves and petiole) were obtained from an experimental investigation conducted by Djoudi et al [145] are presented in Table 3.7. The physical properties of DPW are shown in Table 3.8. The bulk density of DPW samples was determined according to the protocol followed by Brouard et al [146] to determine the densities of plant aggregates.

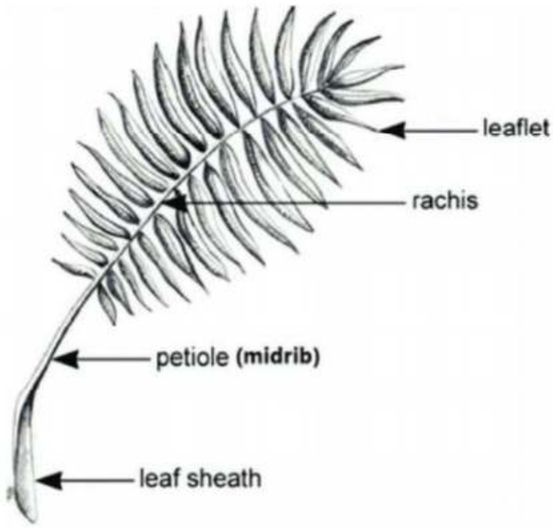


Figure 3. 4: Diagram of date palm frond structure [147]

Table 3. 7: Mechanical properties of DPW fibers (leaves and petiole) used as plant aggregates [145]

Fibers type	Tensil strength σ_{max} (MPa)	ε_{max} (mm/mm)	Modulus of elasticity E (GPa)
Leaves	91.07 ± 17.9	0.008 ± 0.003	13.91 ± 0.76
Petiole	114.53 ± 7.49	0.017 ± 0.005	10.81 ± 0.28

Table 3. 8: Physical properties of DPW

Properties	Sizes mm	Bulk density Kg/m^3
Value	<1	133
	1–5	109
	5-10	103

3.2.5- Water

The water utilized in the combination is drinking water with a temperature of 20±2°C. It is of a quality that conforms with the NFP 18-404 standard for drinking water quality.

3.3- Experiment methodology

Three types of samples were made throughout the testing program: lime content optimization samples, samples containing EPS beads, and samples containing date palm waste.

➢ **Lime optimization specimen fabrication**

The clayey soil was first sieved to 2 mm and dried at 65±2C° for 24 h, to make sure the mixture is dry [12, 148], then it was mixed with different amounts of quicklime (7%, 8%, 9%, 10%, 11%, 12%, 13% by weight) to determine the ideal proportion of quicklime for soil stabilization. The compressive strength of the samples is considered the most important characteristic for determining the ideal ratio of quicklime. The amount of water (W) in the mixture was 26.5% by weight of dry soil to obtain a homogeneous mixture having good plasticity. It was calculated using the formula below:

$$W(\%) = \frac{WL+WP}{2} \quad (3.1)$$

This value, the average of the Atterberg liquidity (WL) and plasticity limits (WP), has been used in previous work [12, 149].

According to [150], every 1% of quicklime introduced into the soil reduces the water content by 1%.

The mixing process begins with mixing the dry ingredients (soil and quicklime) for two minutes, then adding water and mixing manually for 2 min until the paste becomes homogeneous. These mixtures were manually filled into prismatic molds (4x4x16) cm^3 and dried in the open air for 72 hours [12].
Then, the samples were removed from the molds, placed in airtight plastic bags, and cured for 7 days at 65 °C in the oven, according to the procedure proposed by[151]. The optimal value of quicklime content was 10%, as shown in Figure 3.5.

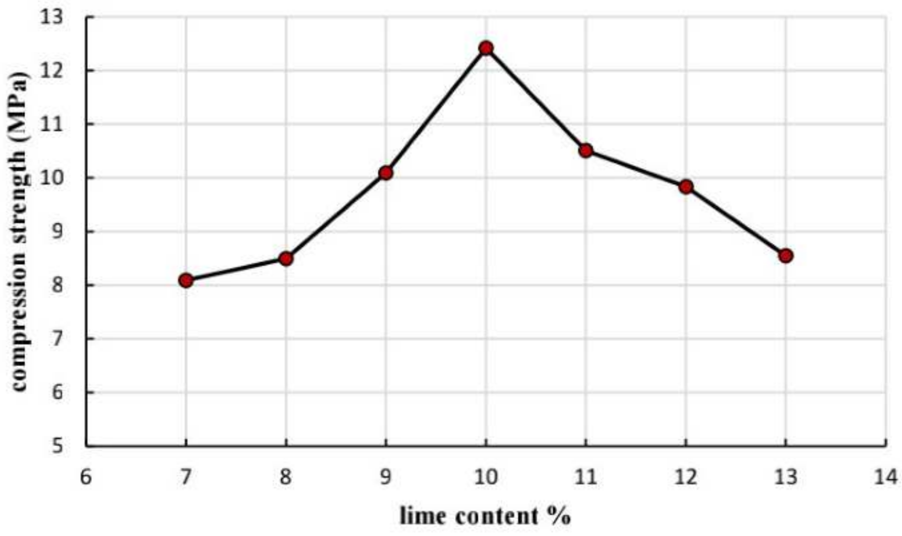


Figure 3. 5: Optimization of lime by dry compression strength.

- **Samples containing EPS beads**

After studying the content of quicklime, LWSs are made based on EPS beads. Dry soil and 10% of quicklime used as a stabilizer (relative to soil weight) were mixed manually for 2 minutes. The determined water content was added in such a way as to achieve a mixture (soil + lime + EPS beads) flow of 170 mm according to the flow table test in order to give similar plasticity to the reference samples [152], and the mixture was stirred for an additional 2 minutes. Then EPS beads in different proportions (40%, 45%, 50%, 55%, 60%, and 65% by volume) were added and mixed until achieving a homogeneous mixture. Table 3.9 shows the mixing volumes for the samples. The same processing steps were followed to improve the quicklime content. Finally, the samples are ready for testing (an average of three samples were taken in each test).

Table 3. 9: Proportion of lightweight samples incorporating EPS beads.

EPS beads		**Soil**		**Lime % (relative to the weight of soil)**		**Water % (relative to the weight of soil + lime)**	
%	Kg/m^3	%	Kg/m^3	%	Kg/m^3	%	Kg/m^3
0	0	100	1341	10	134.10	36.5	489.46
40	4.56	60	804.6	6.0	80.46	26.0	293.68
45	5.13	55	737.55	5.5	73.76	24.0	269.21
50	5.7	50	670.5	5.0	67.05	22.0	244.73
55	6.27	45	603.45	4.5	60.35	19.5	220.26
60	6.84	40	536.4	4.0	53.64	17.5	195.79
65	7.41	35	469.35	3.5	46.94	15.5	171.32

➢ **Samples containing DPW**

The first stage is fiber preparation, where DPW is sieved into three sizes: <1 mm, (1–5) mm, and (5-10) mm. Then it was washed with water to remove dust and impurities, and then dried in an oven at a temperature of 60 °C until dry. After that, the required quantity was weighed, placed in bags with small holes, and immersed in water for 24 hours to ensure that it was saturated with water.

After determining the water content and the optimal stabilizer and preparing the fibers, the second stage is the preparation of the samples. where the soil and 10% of lime are mixed for two minutes, after which water is added and mixed well until homogeneity. After that, DPW is added in different proportions (40%, 45%, 50%, 55%, 60%, 65%, 70%, and 75% by volume) and well mixed manually to ensure the homogeneity of the mixture. The proportions of the different mixtures are shown in Table 3.10. The same curing steps were used to improve the quicklime content. Finally, the samples were tested (we took the average of the three samples).

The highest percentage corresponds to the maximum amount of EPS beads and DPW that may be incorporated in earthen samples due to the loss of mixture workability.

Table 3. 10: Proportion of earthen samples incorporating DPW.

DPW%	Soil %	Lime % (relative to the weight of soil)	Water % (relative to the weight of soil + lime)
0	100	10	36.5
40	60	6.0	21.9
45	55	5.5	20.07
50	50	5.0	18.25
55	45	4.5	16.42
60	40	4.0	14.6
65	35	3.5	12.77
70	30	3.0	10.95
75	25	2.5	09.12

3.4- Measurement methods

This experimental study tested the prepared specimens to bulk density, thermal properties, three-point flexural strength, ultrasonic testing, dry compressive strength tests, and life cycle analysis.

3.4.1- Bulk density

The bulk density of LWS was determined according to the NF EN 771-1 standard using the following relationship:

$$\rho = \frac{M}{V} \quad (3.2)$$

Where (M) is the dry mass in kg and (V) is the volume in m^3.

3.4.2- Ultrasonic pulse velocity test (UPV)

The UPV test is used to determine the influence of adding EPS beads and to know the effect of adding different sizes of DPW on wave transmission speed and time spent on the wave by passing ultrasonic waves through the samples. The test (UPV) was carried out according to Standard NF EN 12 504–4.

3.4.3- Thermal properties

According to ISO 8894–1: 1987[12], thermal conductivity and specific heat (Cp) were measured on brick samples whose dimensions are (10×10×4) cm by CT meter, as depicted in Figure 3.6. The measurements are performed using a hot wire probe and a heating resistor with a sensor that measures the temperature in a transient state. The probe is placed between two smooth-faced samples to avoid contact with air. This measuring technique can be used to determine the thermal conductivity of any water content because it does not cause any change in the water content of the substance.[153].

The Specific heat (Cp), thermal effusivity (e), and volumetric heat capacity (C) were calculated using the expressions below [154]:

$$C = Cp.\rho \quad (3.3)$$

$$e = \sqrt{\lambda.C} \quad (3.4)$$

Where C is the volumetric heat capacity (J.$m^{-3}.K^{-1}$), e is the thermal effusivity ($J.s^{-\frac{1}{2}}.m^{-2}.K^{-1}$), λ is the thermal conductivity ($W.m^{-1}.K^{-1}$), Cp is the specific heat (J.$kg^{-1}.K^{-1}$), and ρ is the bulk density (Kg/m^3).

Figure 3. 6: Thermal properties tester.

3.4.4- Mechanical properties

A Zwick Roell Z050 test machine was used with a load capacity of 100 kN and a loading speed of 0.5 mm/min. In accordance with the NF/EN 771-1 standard, the mechanical behavior in the three-point bending test was performed on specimens with dimensions of $(4 \times 4 \times 16)$cm^3. The flexural strength of three-point bending and the elastic modulus (E) are determined by the following formula:

$$\sigma_f = 1.5 \frac{FL}{bd^2} \quad (3.5)$$

$$Ef = \frac{FL^3}{48I\delta} \quad (3.6)$$

As for the mechanical behavior in compression, the test half-pieces resulting from the three-point bending test are used. The compressive strength is determined according to the standard NF EN 771-1 based on the following relationship:

$$\sigma = \frac{F}{A} \quad (3.7)$$

When σ_f is the flexural strength (MPa), F is the force measured by the testing machine, b and d are respectively the widths and height, and L is the initial specimens' lenght.

σ is the compressive strength (MPa), A is the specimen's initial section area, E is the nominal axial strain, δ is the deflection generated by the load F that is measured by the testing machine, I is the moment of inertia of the section at mid-span.

Figure 3. 7: Mechanical test device (bending and compression behavior)

3.4.5- Preparation of samples for the microscopic studies

To prepare a sample from lightweight earth samples for Scanning Electron Microscopy (SEM), follow these steps:

Cut a small piece of the block with a sharp, clean cutting tool. Mount the sample on an SEM stub using a conductive adhesive such as carbon tape or silver paint.

Coat the sample with a thin layer of conductive material, such as gold or gold/palladium, to improve the imaging and reduce charging during the SEM analysis. This can be done using a sputter coater.

Load the stub into the SEM chamber and analyze the sample under high vacuum.

It is important to wear appropriate personal protective equipment, such as gloves, when handling the sample to avoid contamination. It is also important to ensure the sample is properly cleaned and free of contaminants prior to analysis, as they can affect the imaging quality and accuracy.

3.4.6- Life Cycle Analysis (LCA)

Since 1994, Life Cycle Analysis (LCA) has been used to evaluate the environmental effects of a product or process from the extraction of raw materials to its end-of-life treatment (landfill, recycling, etc.), or "cradle to grave." This methodology is scientifically recognized and standardized (by ISO standards 14040 to 14043)[155]. LCA is a method for determining how an activity or product affects the environment throughout the duration of its whole life cycle (construction, use, renovation, and demolition) [156]. As demonstrated in Figure 3.8, the construction and renovation phases include the fabrication and transportation of building materials and technological installations utilized in building construction and renovation. The operation phase encompasses all actions linked to using buildings during their lifetime (heating, air conditioning, ventilation, lighting, hot water, and operation of appliances). Finally, the demolition phase involves dismantling the structure and transferring the deconstructed materials to landfills or recycling centres[155]. The boundary for the LCA analysis in this study is the entire life cycle of a building, from its construction to its demolition. The analysis takes into account various variables to determine the impact of the building on the environment, including:

- Energy consumption: The study calculates the total energy consumption for heating, air conditioning, ventilation, lighting, and other building operations.
- Building materials: The types of materials used for construction and insulation, including air blade and expanded polystyrene, are considered.
- Climate: The hot and dry climate of Biskra, Algeria, where the building is located, is taken into account with meteorological information and temperature data.
- Building occupancy: The study considers the use and occupancy scenarios of the building, such as the internal temperature, ventilation, and energy dissipation.
- Building's life span: The study assumes an analytical life of 80 years for the building's construction.
- Simulation tools: The study uses the Comfie-Pleiades and Nova-Equer simulation software to model the building and analyze its impact on the environment.

These variables are considered to determine the impact of the building's construction and operation on the environment and to evaluate the energy performance and environmental impact of various insulation configurations for exterior walls. The variables considered for analysis are all the thermal and environmental characteristics of the material, its dimensions and thicknesses, as well as its location according to the chosen construction technique.

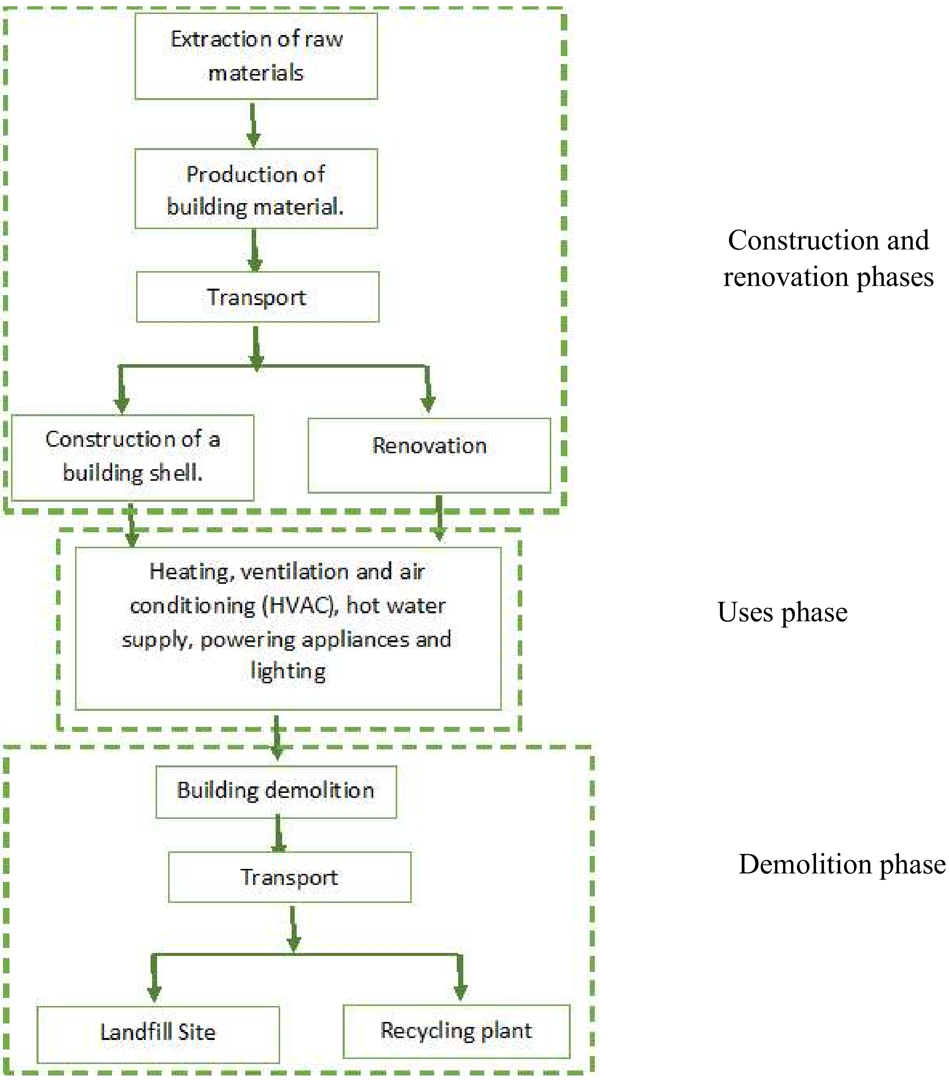


Figure 3. 8: Phases of Life Cycle analysis [2]

This method relies on a four-step process (Figure 3.9):

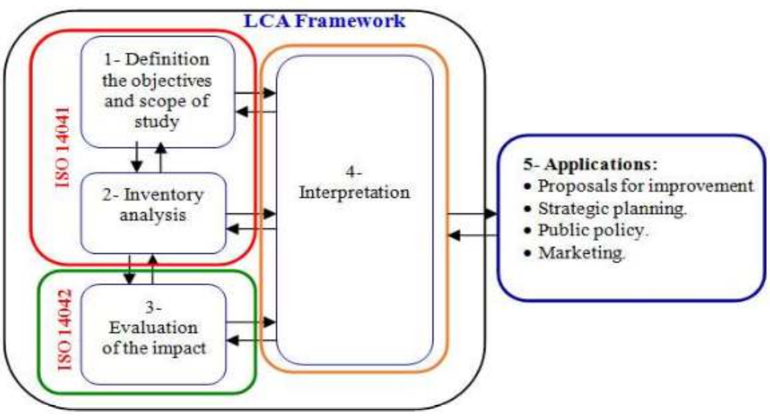


Figure 3. 9: Framework for a LCA

3.4.6.1- Life Cycle Analysis Objectives

The objective of this investigation is to obtain life cycle analysis results of numerous exterior wall configurations [155], which will:

a) Calculate the total energy consumption (lighting, heating, air conditioning, ventilation, etc).

b) Make energy optimization to identify all environmental effects throughout the construction's life cycle.

c) Evaluate the environmental adaptation of the building to the dry, hot climate.

3.4.6.2- Biskra, Study Context

Biskra represents all Algerian cities, the arid area with dry and hot weather.

Characterized by:

1. The highest temperatures of around 45.2°C are registered in the summer and July.
2. The lowest temperatures, around 2.2 °C, are registered in winter and January.
3. The temperature variation between day and night is 15°C.
4. Strong insulation exceeding 3500h/year.
5. High levels of direct sun radiation range from 900 to 1100 W/m².
6. Relative humidity remains low at 27%.
7. Winds can reach up to 80 km/h during the half-seasons.

3.4.6.3- Simulation

This LCA is an experimental study that uses informatics simulation. The experiment used the Comfie-Pleiades dynamic heat behavior modeling tool (version 3.6.9.0, 2016), which is coupled to the building environmental impact analysis software, nova-Equer (version 1.6.9.0, 2016).

Simulation tools

The Alcyone program specifies all of the building data (materials, geometry, etc.) and site data (direction, neighborhood, environment, near masks), as well as meteorological information from Biskra city, or "meteor norms,"(version 7.1.0.0, 2016) as information for the simulation.

Comfie-Pleiades is the dynamic thermal simulation DTS software for buildings [157]. The program calculates energy needs based on data from building materials, occupancy situations, and meteorological factors. The energy requirements have already been evaluated and submitted to Nova-Equer the building's environmental impact assessment instrument [158].

- **Simulation Protocol**

A first simulation involves changing the nature, source, and type of insulation used in the construction of exterior walls (air blade, expanded polystyrene).

The thermal study and environmental analysis results will allow the comparison of the various configurations. As a result, the insulation evaluated in this stapes of the work has been validated [159].

Such drives include [160]:

a) The insulating implementation method will decide the thermal performance levels of the construction.

b) Optimizations of energy.

c) Environmental impacts.

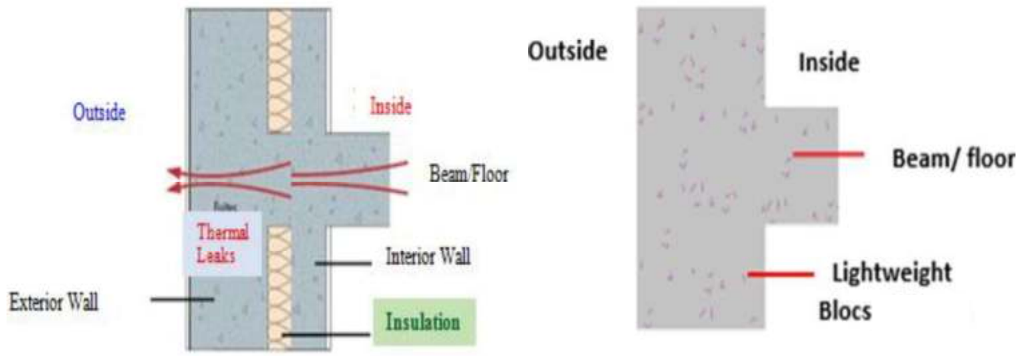


Figure 3. 10: Distributed Insulation of exterior walls.

The category is determined based on simulation results for environmental effects and energy performance, as indicated in Table 3.11.

Table 3. 11: Evaluated environmental indicators.

Environmental Indicator	Unite
Greenhouse effect	t CO2 eq.
Acidification	kg SO2 eq.
Cumulative Energy Demand	GJ
Water used	m^3
Inert waste produced	T
Exhaustion of ambiotic resources	kg E-15
Eutrophication	kg PO4 eq.
Ozone production photochemical	kg ethylene eq.
Aquatic ecotoxicity	m^3
Radioactive waste	dm^3
Human toxicity	kg
Odor	m^3 air

- **The simulation reasons**

In this study, a new building is modeled to determine the best insulating materials for its envelope. For this objective, a functional unit of 1.00 m^2 of landscaped office space was chosen.

This part contains the concrete construction elements, the envelope materials, the internal separators, the paints, the coatings, the woodwork, and the glazing type (mono or double-glazing).

The basic level of modeling involves assessing the building in its primary state, including all technological solutions, components, and therapies ((dual walls, structural, individual glazing bays, power systems, etc).

Additional insulation was considered, Because of its outstanding thermal and environmental properties.

EPS beads is a synthetic material commonly employed in the building sector, offered on the marketplace with varying thicknesses and approachable unit pricing.

3.4.6.4- Use and occupancy scenarios

The essential energy simulation criteria that apply to all building envelope configurations are as follows [156]:

1. Perpetual Temperature of 20°C.
2. Regular ventilation and over-ventilation during summer.

3. The case of heating: 20°C (and cease at night)
4. The Case of Air Conditioning: 25°C (with a halt at night)
5. Energy dissipation case: 4100 W.
6. Office utilization is 100% between 08.00 Am and 05.00 PM, and 00% the remainder of the day.
7. Internal inputs are 40 Wh/m².

The requirements for the building's LCA environmental study are the following:

a) The analytic life of the construction is 80 years.
b) An equipment's lifetime is 20 years.
c) Woodworking takes 30 years.
d) 10 years for paint.

Additionally, a gas heating system is regarded as electric air conditioning.

3.5- Conclusion

This chapter focused on a comprehensive description of the materials used in this study, encompassing their chemical, physical, and mechanical properties. In addition, the formulation of earthen samples stabilized by lime and incorporated expanded polystyrene beads and date palm waste, as well as the methods and standards used to characterize them, were presented.

Chapter

4

RESULTS AND DISCUSSION

Chapter 4

Results and discussion

4.1- Introduction

Previous studies have explored the potential use of EPS and DPW materials as thermal insulation components in buildings. Therefore, this chapter focuses on studying the physical, thermal, and mechanical properties of lightweight earth samples stabilized with lime. Note that the experimental work on manufactured lightweight earth samples was divided into two main parts. The first part was devoted to studying the effect of incorporating different proportions of EPS beads into lightweight earth samples on the physical, thermal, and mechanical properties, in addition to studying the life cycle analysis of external walls that were constructed using lightweight earth samples stabilized with lime and containing 50% and 65% of EPS beads, to evaluate their environmental impact. The second part was devoted to studying the effect of incorporating different proportions and sizes of DPW content on the physical, thermal, and mechanical properties of lightweight earth samples stabilized with lime.

4.2- Effect of the incorporation of synthetic aggregates into earthen samples

4.2.1- Effect of EPS beads content on the physical properties of lightweight samples (LWS)

4.2.1.1- The apparent density

The results of the material's apparent density are shown in Figure 4.1. It was found that the apparent density dropped from 1505.43Kg/m^3 when 0% of EPS beads to 568.51kg/m^3 at 65% of EPS beads. It was noted that the density value decreases as the EPS beads percentage increases, reaching a decrease of 62.24% and 48.67% at the content 65% and 40% of EPS beads respectively compared to the sample without EPS beads (0% of EPS beads). This decrease is attributable to the ultra-lightweight of the EPS beads; the average density of EPS beads particles is 11.4 Kg/m^3.

Reduction of apparent density by adding the quantum of EPS beads has been declared by Nikbin et al.[20] when the bulk density of EPS concrete ranges from 2312 to 1611 kg/ m^3, which is lower than the bulk density of plain concrete. The explanation for this drop is that EPS beads have a lower specific gravity than natural aggregates. Dixit et al.[5], It was found that the apparent density of cement composites with EPS decreased by 36% com pared to the reference mixture. The same trends were reported for the plant aggregates in the study by Laborel et al. [80]. Also, when the quantity of straw, hemp, and corncob in the soil combination increased, the bulk density decreased.

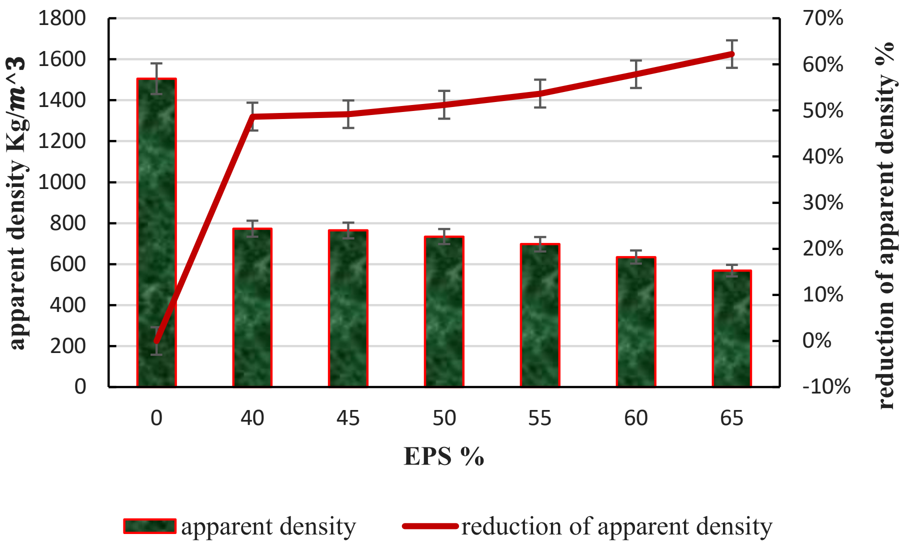


Figure 4. 1: The apparent density of LWS as a function of the percentage of EPS beads.

4.2.1.2- Ultrasonic pulse velocity (UPV)

Ultrasound velocity is a non-destructive method for measuring the material's sound speed, considering that the speed of waves is a function of the porosity inside the material. When the ultrasound propagation velocity test results were analyzed, as shown in Figure 4.2, it was discovered that when the amount of EPS beads in the earth matrix increased, the wave propagation velocity dropped significantly. It noticed that the value of ultrasound propagation velocity dropped from 1345 m/s (for 0% EPS beads) to 310 m/s (for 65% EPS beads). In fact, among all the samples, the ultrasonic pulse velocity value of the sample with 65% EPS beads is the lowest. Compared with the sample without EPS beads, this value is reduced by 76.95%. This reduction in ultrasonic pulses may be explained by the fact that EPS beads have a better sound insulation coefficient than earth concrete. Additionally, the enhancement of porosity results from the increased content of incorporated EPS beads, which are mainly filled with air, contributes to this phenomenon. Similar patterns were discovered in the study carried out by Nikbin et al. [20], who discovered that the ultrasonic wave speed of EPS cement concrete reduced as the amount of EPS increased.

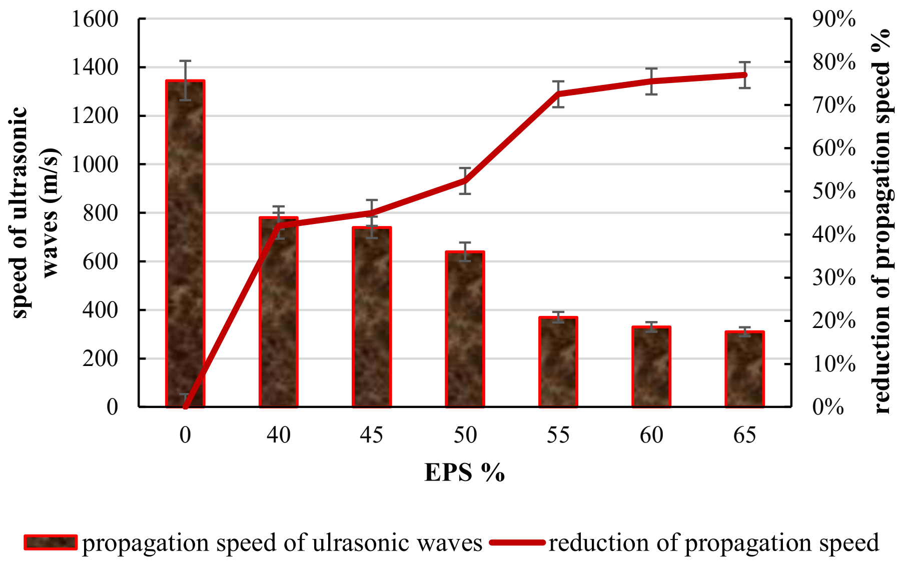


Figure 4. 2: Variation of ultrasonic pulse velocity of LWS as a function of the percentage of EPS beads

4.2.2- Effect of EPS beads content on the thermal properties of LWS

4.2.2.1- Thermal conductivity (TC)

Figure 4.3 depicts the variation in TC with various percentages of EPS beads. The presence of EPS beads in samples made of raw earth caused significant decreases in TC. The incorporation of 40% and 65% of EPS beads resulted in lower TC by 47.19% and 57.36%, respectively, compared with control samples (without EPS beads), which are valued at 0.462 W/m.C°. In addition, it decreased by 19.26% when the EPS beads ranged from 40% to 65%. This decrease is predicted due to the EPS beads have a lower TC, which ranges between 0.03863W/m.C° and 0.03365 W/m.C° as conducted by [151], compared to the soil matrix.

In contrast hand, the decline in the bulk density of LWS, as shown in Figure 4.4, is caused by a rise in the proportion of EPS beads, which has a lower density than the clay matrix (bulk density of EPS beads and bulk density of soil are 0.0114 g/cm^3 and 1.341 g/cm^3 respectively). The porosity factor also affects the TC of the samples, as closed pores decrease the TC due to the low TC of air [4]. The incorporation of EPS beads increases the porosity, resulting in a reduction in TC [161].

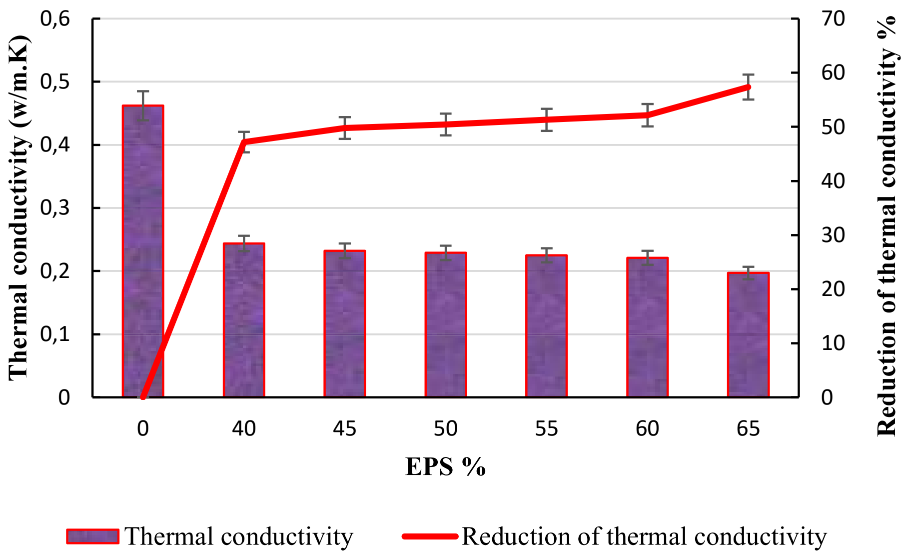


Figure 4. 3: TC of LWS as a function of EPS beads content

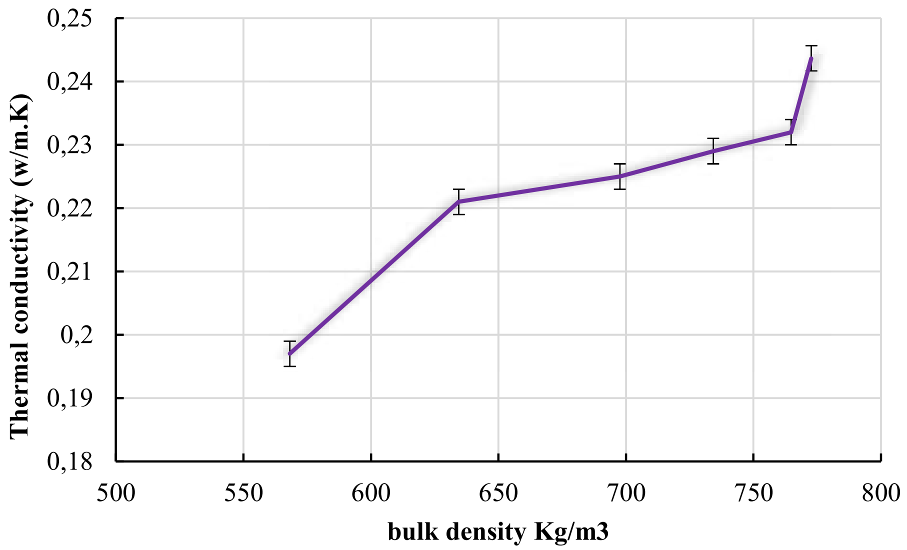


Figure 4. 4: TC of LWS incorporating EPS as a function of bulk density.

4.2.2.2- Specific heat capacity

Specific heat capacity evaluation of LWS made by raw earth incorporating EPS beads is presented in Figure 4.5. It was noted that when EPS beads rises from 40% to 55%, the specific heat capacity increases from 576.7 J/kg.K to 669.6 J/kg.K by 16.11%. Then, a significant decrease in the specific heat capacity at a content of 60% and 65% of EPS beads. The same behavior was reported by Khoudja et al. [12]. According to Khoudja et al. [12] this rise in specific heat may be explained by the integration of this particle (EPS beads), whose specific heat is greater than that of the reference clay block containing just lime and sand. The reason for the decrease in the specific heat of the material is due to the enhancement of the porosity (resulting from the increase in the incorporating content), which is mainly filled with air.

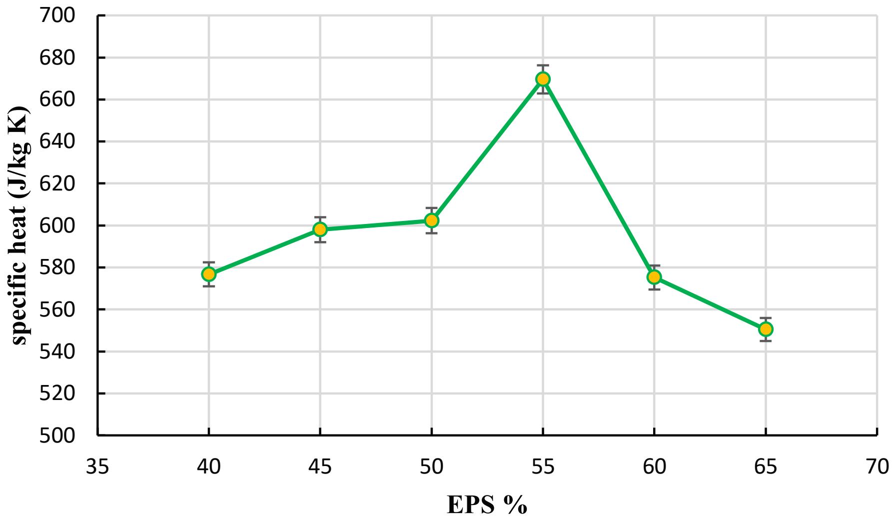


Figure 4. 5: Specific heat of lightweight samples as a function of EPS beads content.

4.2.2.3- Thermal effusivity

One of the important concepts concerning the efficiency of thermal insulation is thermal effusivity. It characterizes a material's surface's capacity to absorb and release heat. Figure 4.6 demonstrates the variation of thermal effusivity. This figure illustrates that as the content of EPS beads increases, the thermal effusivity of LWS decreases. Specifically, there is a 75.5% reduction when adding 65% EPS beads compared to the reference samples, and a 24.66% decrease in thermal effusivity for EPS beads content ranging from 40% to 65%. These findings suggest that LWS exhibits a reduced ability to exchange heat with its environment compared to the reference samples. The same result was declared by Atiki et al.[97], who investigated compressed earth samples containing date palm waste aggregates, and those found by Boumhaout et al. [162], who researched cement mortar incorporating palm mesh fibers.

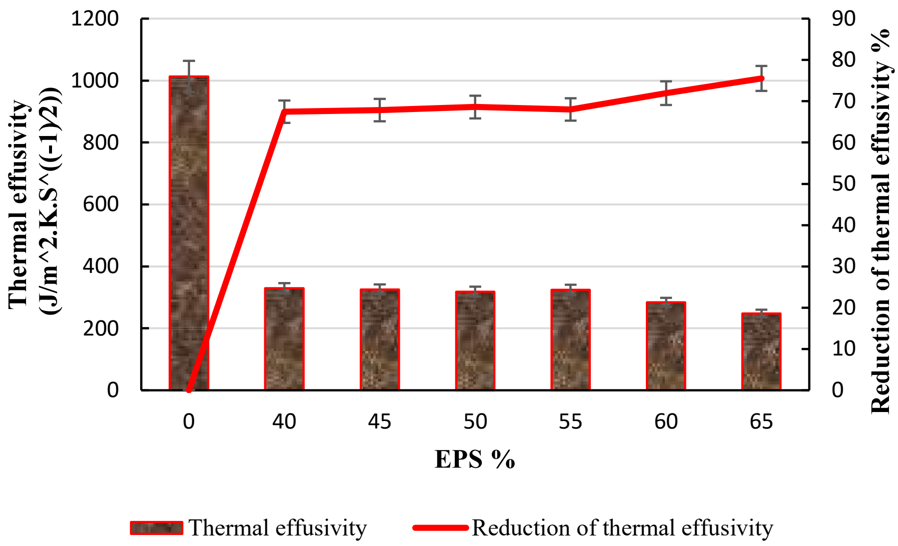


Figure 4. 6: Thermal effusivity of LWS as a function of EPS beads content.

4.2.2.4- Volumetric heat capacity

The VHC is a critical indicator for determining the thermal inertia of building materials. Figure 4.7 illustrates the evolution of the lightweight block's VHC. It was found that the VHC ranges between 2.223 Mj/m3.K for the reference sample (0% of EPS beads) to 0.313 Mj/m3.K for the sample with 65% of EPS beads. The VHC dropped from 79.96% to 85.93% when EPS beads increased from 40% to 65% compared to the reference block (0% EPS beads), respectively. A similar finding was reported by Karrech et al.[163], who revealed that the different proportions of lightweight aggregates affect the VHC of cement stabilized rammed earth. The results indicate that the VHC reduces when the volume fraction of polystyrene increases. Additionally, a similar finding for the VHC trend was noticed by Atiki et al [97].

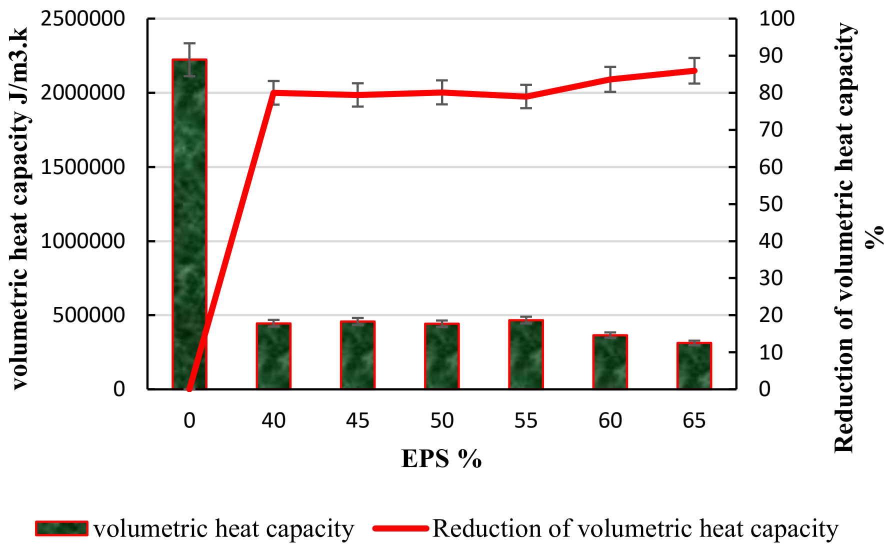


Figure 4. 7: VHC of LWS as a function of EPS beads content.

4.2.3- Effect of EPS beads content on the mechanical behavior of LWS

4.2.3.1- Dry compressive strength

Mechanical behavior is among the most significant features of construction materials. Figure 4.8 and Figure 4.9 present the influence of EPS beads content on the mechanical behavior of LWS made by raw earth. Table 4.1 summarizes the mechanical parameters (compressive strength, elastic modulus, and ultimate strain). It was observed that the compressive stress-strain curves of all test pieces could be divided into two phases. In the first phase, whenever the compressive force is applied, the sample behaves semi-linearly, which indicates the elasticity of the material at this stage until it reaches the maximum stress value. It is followed by the weakening stage, where the stress decreases until it reaches a stage where the stress value becomes nearly constant, and the deformation is significant. This is known as the ductility of the material, which is due to the polystyrene content. Furthermore, it can be concluded that LWS made from raw earth containing EPS beads have better ductility than samples without EPS beads and a higher capacity of energy absorption under compression load. The LWS containing EPS beads failed gradually, and the samples were able to sustain the load after failure without complete disintegration [4], compared to samples that did not contain EPS beads, as shown in Figure 4.10. The good energy absorption quality of EPS beads is mainly responsible for the gradual breakdown of LWS. Similar findings were obtained by Bing Chen et al. [4], who showed that the failures of the EPS beads foam concrete samples were gradual and that it was able to maintain the load after failure without complete disintegration. Unlike normal-weight concrete. Moreover, a decrease in stress can be noticed when the polystyrene content rises. Figure 4.11 demonstrates the compressive strength of LWS of raw earth incorporating different concentrations of EPS beads. As can be shown, the compressive strength reduces by approximately 69.87% when the EPS beads content is increased from 40% to 65%, or from 1.404 MPa to 0.423 MPa, respectively. The compressive strength value of the samples without EPS beads was estimated at 12.42 MPa. Compared to the reference sample (without EPS beads), the compressive strength decreased by about 96.59% for the sample containing 65% of EPS beads. The nature of the EPS beads incorporated in the soil matrix and their weak compressive strength are the cause of the samples' poor mechanical properties. Despite the better adhesion of the EPS beads to the soil matrix, as illustrated in Figure 4.12(b) [164]. Also due to the pores in EPS beads and clay, as indicated by Kaya and Kar [26], who showed that pores improve TC but decrease mechanical characteristics.

Additionally, samples that include 40% to 50% EPS beads comply with Turkish standards. (Turkish Standards Institution, Ankara, 1985-TSE: Adobe Molds and Production Methods TS 2514). A compressive strength threshold of 1 MPa is required.[165].

In the same context, Maarouf et al. [16] examined the influence of expanded polystyrene-based mortar on compressive strength. The results demonstrate that the compressive strength dropped from 22.5 MPa for the sample without EPS to 4 MPa for mortar containing 53% EPS. The polystyrene mortar represents an 80% reduction. In addition, these results agree well with the results of previous research that demonstrated that the mechanical strength drops with increasing plant particles content [80].

In addition, researchers have demonstrated that the higher the natural fiber content, the lower the compressive and tensile strength [166]. As a result, the decreased compressive strength can be justified by the inclusions' lower mechanical strength and the matrix's higher porosity, as demonstrated in Figure 4.12(a).

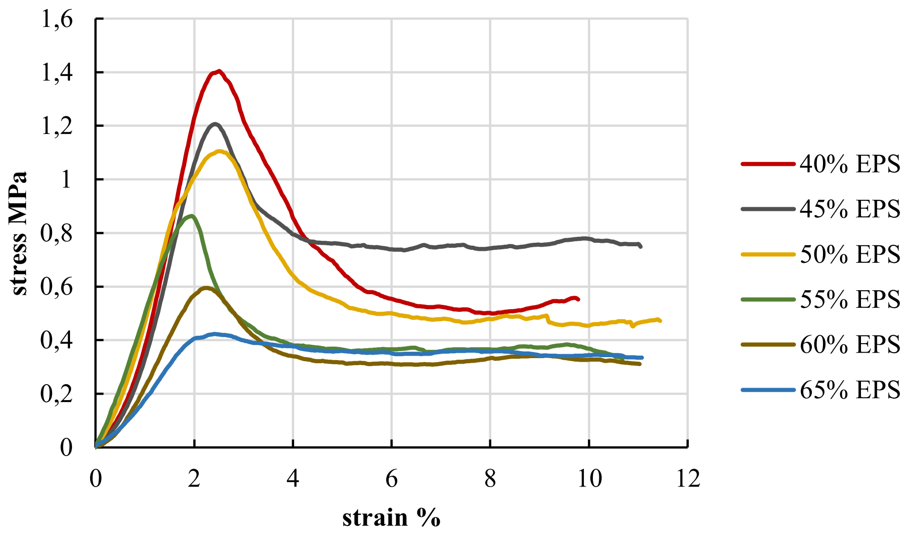


Figure 4. 8: Effect of EPS content on the mechanical behavior.

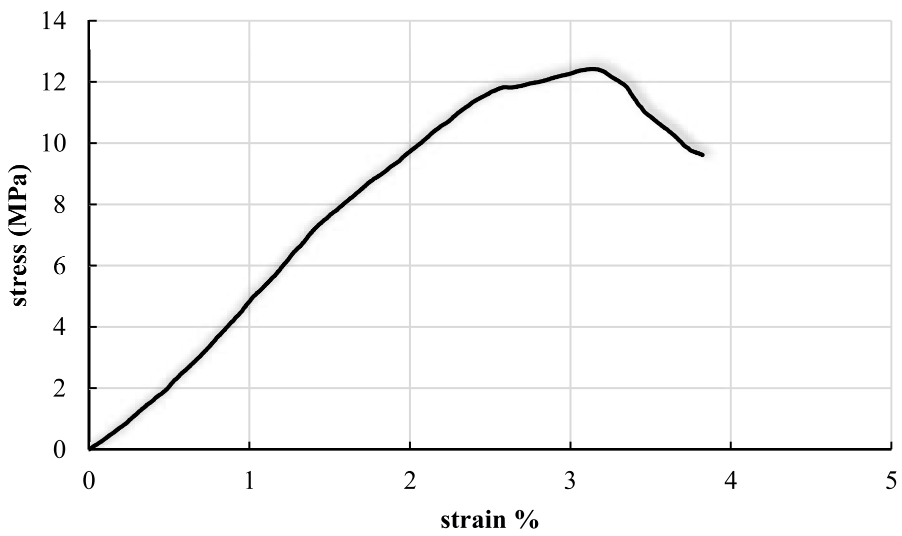


Figure 4. 9: Mechanical behavior of the reference sample (0% of EPS beads).

Figure 4. 10: Specimen after failure under flexural and compressive test.

The compressive strength, elastic modulus, and ultimate strain are summarized in Table 4.1. The results demonstrate that the modulus of elasticity decreases when the EPS beads increases, dropping from 88.073MPa for bricks content of 40% of EPS beads to 25.389 MPa for bricks content of 65% of EPS beads as illustrated in Figure 4.13. In the same context, Kaya and Kar [161] found that the elastic modulus of the composites dropped as the polystyrene content rose, involving greater flexibility of the plaster matrix. Furthermore, Nikbin et al. [20] discovered that the young modulus of EPS concrete decreases with increasing EPS content for both water-cement ratios. The ultimate strain is shown in Table 4.1. The results show that the ultimate strain of the reference samples is greater than the lightweight samples containing EPS beads. This is due to the high- strength of the reference samples, which led to larger ultimate strain, in contrast to the samples containing EPS beads, which were characterized by a low- strength, which led to small ultimate strain.

On the other hand, it can explain the decrease in the ultimate strain to the high percentage of the EPS beads content in the samples, which reached 65%, which led to a reduction in stress followed by a decrease in the ultimate strain. In contrast to the results obtained by [12], where the percentage of palm fibers was few, not exceeding 10% compared to the soil matrix, the results showed a high ultimate strain of the samples, containing 8% and 10% compared to the reference samples.

Table 4. 1: Mechanical parameters in compression of LWS.

EPS beads %	contrainte	Elastic modulus (MPa)	Ultimate strain %
0	12.42	388.82	3.14
40	1.404	88.073	2.465
45	1.207	76.421	2.465
50	1.105	69.158	2.557
55	0.863	55.632	1.955
60	0.594	36.32	2.365
65	0.423	25.389	2.455

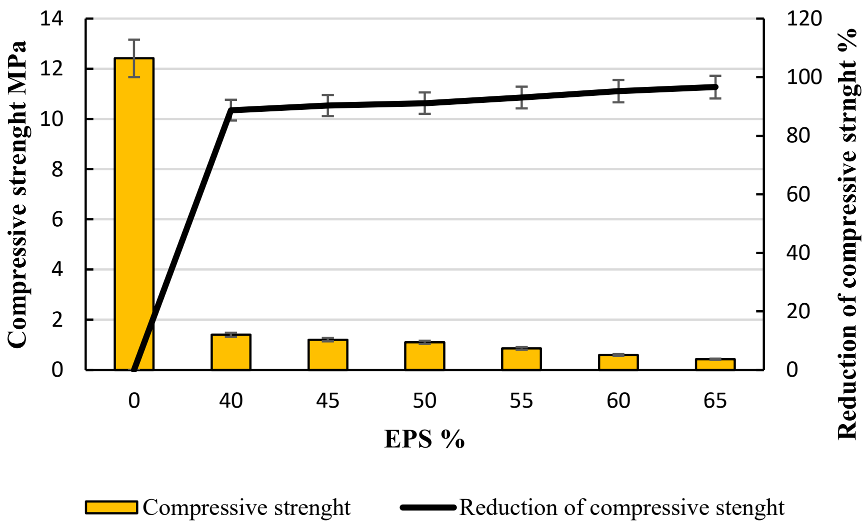


Figure 4. 11: Effect of EPS beads content on the dry compressive strength of LWS.

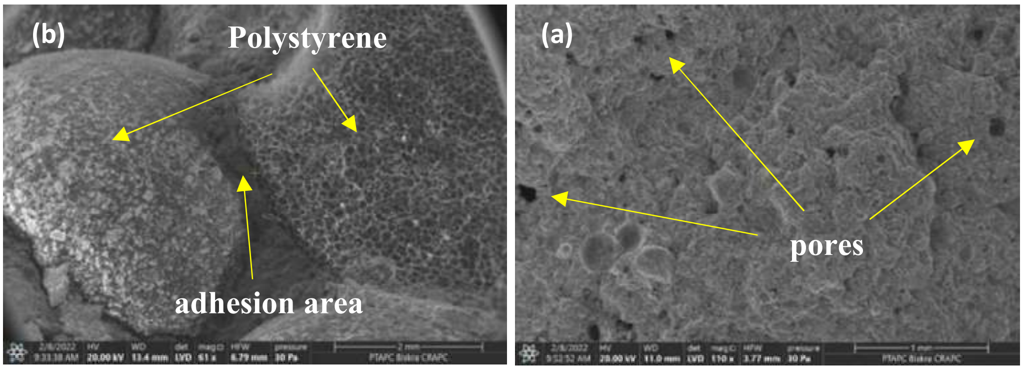


Figure 4. 12: SEM images of samples: (a) Without EPS beads, (b) With EPS beads

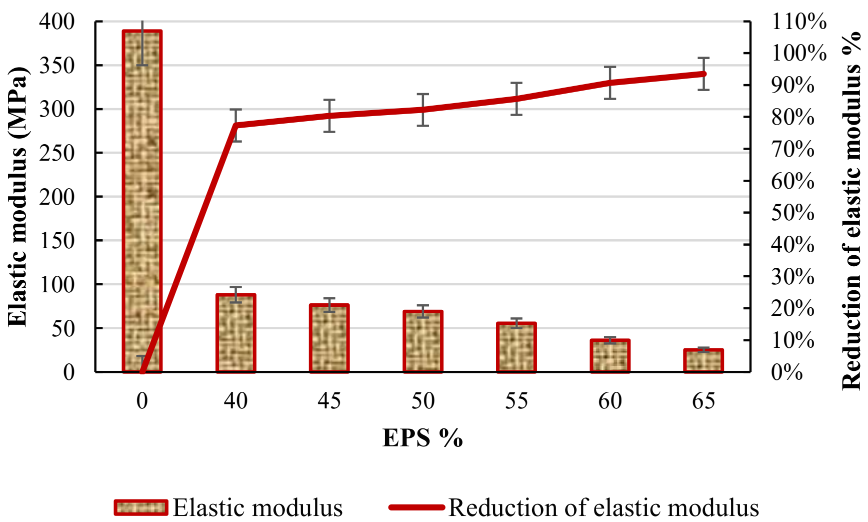


Figure 4. 13: Modulus of elastisity of LWS as a function of EPS beads content.

4.2.3.2- Flexural behavior

A three-point flexural test was performed to understand better the mechanical behavior of samples containing EPS beads. The load-deflection curves and ultimate strain (flexural strength) are depicted in Figure 4.14 and Figure 4.15.

According to the results, all samples exhibit linear elastic behavior and then weaken until they reach their maximum value, followed by a decrease in load accompanied by plastic deformation. However, the reference samples (0% of EPS beads) show linear elastic behavior up to the maximum value, followed by brittle failure. Furthermore, it should be noted that the two parts of the sample containing polystyrene did not disintegrate immediately due to the presence of EPS beads in the soil matrix prevented the possibility of brittle fracture, as depicted in Figure 4.10. Unlike samples that do not contain polystyrene beads. Figure 4.16 represents a decrease in the mechanical performance of three-point bending strength with an increase in the percentage of EPS beads estimated at 75.60% for samples containing 40% EPS beads compared to the reference samples and with a value estimated at 90.50% for samples containing 65% of EPS beads as it decreased from 2.39 MPa, 0.583MPa and 0.227MPa respectively.

and Figure 4.17 include the results of the modulus of elasticity for the samples. Moreover, it dropped by 61.06%, from 40% to 65%. The bending elastic modulus of the samples decreased from 221.62 MPa to 20.112 MPa, which confirms the ductile behavior of the LWS compared to the reference sample. In addition, it should be noted that the presence of EPS beads confers the samples an increase in the ultimate deflection.

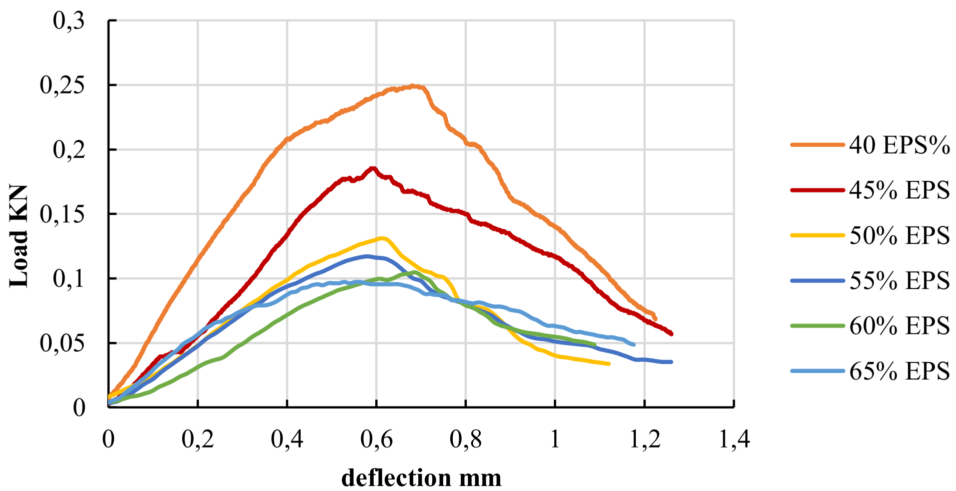


Figure 4. 14: Effect of EPS beads content on the Flexural load-deflection

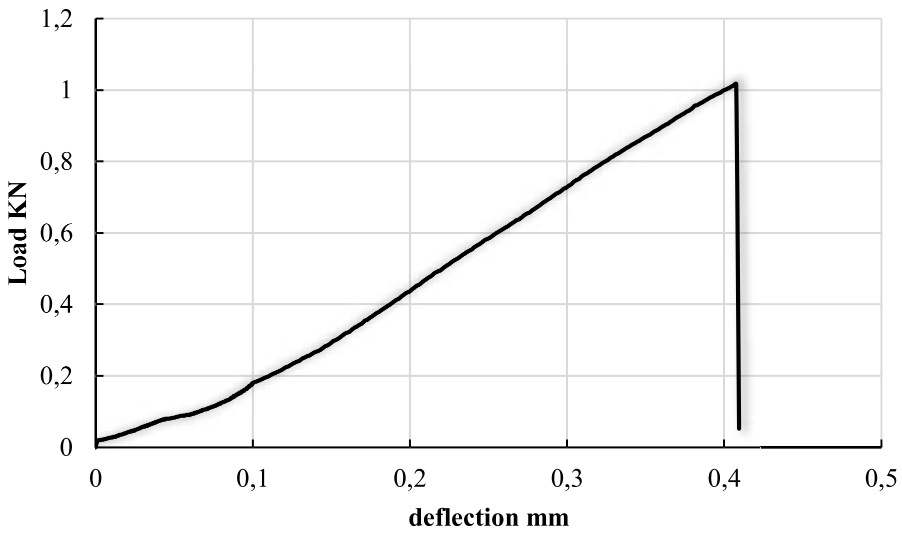


Figure 4. 15: Flexural load-deflection of the reference sample (0% of EPS beads).

Table 4. 2: Mechanical parameters in flexural of LWS.

EPS %	Load KN	Ultimate stress MPa	Elastic modulus MPa	Ultimate deflection mm
0	1.020	2.390	221.62	0.406
40	0.249	0.583	44.953	0.68
45	0.185	0.433	35.318	0.60
50	0.131	0.307	27.222	0.61
55	0.117	0.274	24.17	0.58
60	0.104	0.245	21.537	0.69
65	0.097	0.227	20.112	0.612

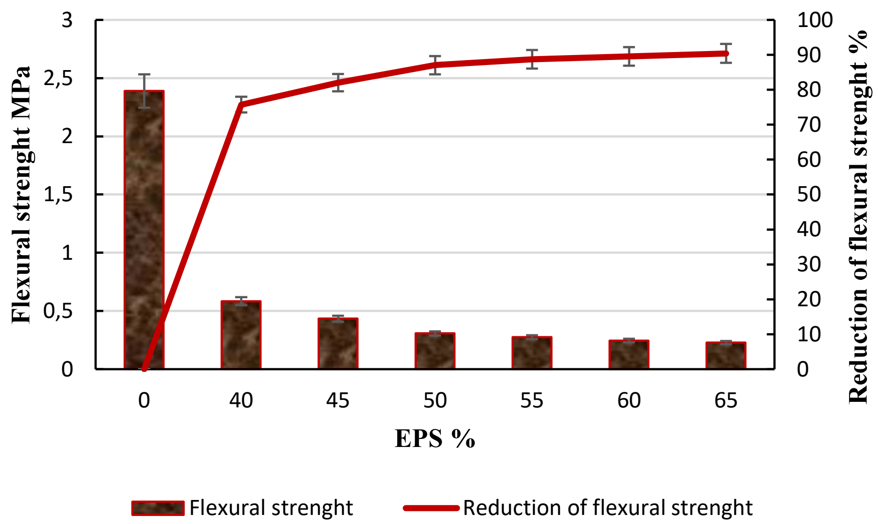


Figure 4. 16: Effect of EPS beads content on the flexural strength of LWS.

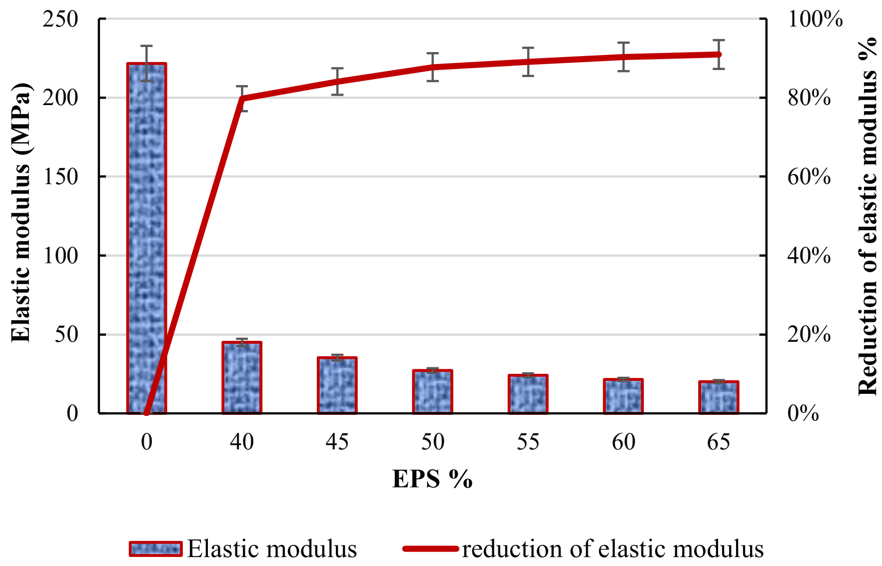


Figure 4. 17: Flexural elastic modulus of LWS as a function of EPS beads content.

Figure 4. 18: Energy-dispersive x-ray spectroscopy of LWS: (a) Without EPS beads, (b) With EPS beads

The main reasons for the drop in the mechanical performance of bending, compression, and modulus of elasticity is the reduction in the content of the binder (soil and lime) and the increase in the amount of EPS beads in the mixtures. This led to a decline in silicate hydrates (measured as Si) and calcium, which produced a fall in the amount of C-S-H within the samples, which are important for the strength of the samples [97], as shown in Figure 4.18. On the other hand, owing to the inadequate compressive strength of EPS beads.

4.2.4- Life Cycle Analysis

A first classification is established based on the materials' thermal, technical, and insulating properties, as shown in Table 4.3, and their related environmental balances, as illustrated in Table 4.4.

Table 4. 3: Technical insulation characteristics

Characteristics / Insulation	Technical Characteristics				
	Thickness (cm)	Thermal resistance R (m2.°C/W)	Density (kg/m3)	Specific heat (kJ/kg.K)	Resistance to water vapour diffusion Sd (m)
Air blade (Non-ventilated)	5.0	0.16 [167]	1	1000	0
Lightweight Samples with Expanded Polystyrene 65%	30.0	1.52	568.51	550.4	20
Lightweight Samples with Expanded Polystyrene 50%	30.0	1.31	734.223	602.3	18

Table 4. 4: Insulation environmental characteristics.

Characteristics / Insulation	Environmental Assessment				
	Grey energy used (kWh/m^3))	Greenhouse effect (kgCO2/UF)	Hygroscopic capacity	Time of Phase Shift Hour	Comfort of Summer Obtained
Air blade	/	No	No	03	06/20
Lightweight Samples with Expanded Polystyrene 65%	450	10	No	12	14/20
Lightweight Samples with Expanded Polystyrene 50%	575	13	No	11	12/20

According to the life cycle analysis, the results are given in the form of 12 environmental indicators, which are Basic Energy Demand, Water Consumption, Atmospheric effects, Human health, resource depletion, and solid waste.

Atmospheric effects are represented by atmospheric acidification (kg SO_2 eq), photochemical ozone, production (kg ethylene eq), and greenhouse effect (kg CO_2 eq).

The terms used to describe the effects on the water are water used (m^3), eutrophication (kg $(PO_4)3$), and aquatic environmental toxicity.

Human health is expressed by human toxicity (kg) and odor (air mm^3).

The effect of resource depletion is also indicated by the depletion of abiotic resources (kg E-15).

Solid waste is also taken into account, which is the production of inert waste (t) and radioactive waste (dm^3).

Table 4. 5: Environmental impact of wall composition

Insulation / Environmental Impact	Air blade	Lightweight Samples With E PS 50%	Lightweight Samples With E PS 65%
Greenhouse effect (t CO2 eq.)	697.21	652,19	586.65
Acidification (kg SO2 eq.)	2619.51	2554,39	2324.18
Cumulative Energy Demand (GJ)	26920.88	23665,67	21585.12
Water used (m³)	45 821.18	42009,35	37519.84
Inert waste produced (t)	476.58	461,32	453.43
Exhaustion of abiotic resources (kg E-15)	11.22	10.13	9.93
Eutrophication (kg PO4 eq.)	854.80	842.72	820.81
Ozone production Photochemical (kg ethylene eq.)	1390.97	1136,24	1173.57
Aquatic ecotoxicity (m³)	14 916 261.98	13110925,76	13 908 914.16
Radioactive waste (dm³)	53.18	50,31	44.35
Human toxicity (kg)	3413.08	2901,68	3 007.39
Odor (m³ air)	6570.37	4624,05	4845.60

Several environmental parameters of exterior walls are summarized in Table 4.5 and Figure 4.19. It can be seen that the environmental impact of lightweight walls made of EPS beads has less effect than the conventional wall insulated with air blades. In general, lightweight walls require less energy than conventional air blade walls. This decrease is estimated at 12.09% and 19.82% for walls made of LWS (50% and 65% of EPS beads), respectively, compared to conventional air blade walls. It can be further explained by observing the environmental effects of the life cycle phases of the various walls, as demonstrated in Table 4.6, Table 4.7, and Table 4.8.

There is a clear difference in the energy consumption of the office life cycle between lightweight walls and conventional walls due to the construction and lower energy usage of lightweight walls compared to conventional walls, as shown in Table 4.6, Table 4.7, and Table 4.8. This can be attributed to the fabrication method of building materials. As the LWS are made of soil, a local resource and EPS beads is available. And require a small amount of energy in the process of industry and transportation. Whereas hollow clay bricks require kilns in their manufacture as they are processed in a kiln at a high temperature to harden and thus require large amounts of energy. Although embodied energy (energy consumption) accounts for only 10–20% of the total life cycle energy, the possibility of its reduction should not be overlooked. There is potential for lower embodied energy requirements through the use of building materials that require less energy during manufacturing [168, 169]. In this context, Shukla et al. [56, 170] evaluated the embodied energy of an adobe house. The house was built using low-energy materials such as soil, sand, and cow dung. It should be noted that the embodied energy of an adobe house decreases by 50% compared to a traditional concrete house. This reduction was achieved through the use of lower-energy and locally available materials (such as soil, sand, cow dung, etc.) than fired clay bricks, concrete, cement, etc.

The lower energy use is attributed to the good thermal resistance of the LWS walls of 1.31 $m^2.^oC/W$ and 1.52 $m^2.^oC/W$ for the content (50% and 65%) of EPS beads, respectively, which requires less energy to maintain comfortable conditions inside the building compared to conventional walls with a thermal resistance of 0.619 $m^2.^oC/W$. A decrease of about 11.85% and 19.48% in the energy used for walls with a content of 50 % and 65% of EPS beads was observed.

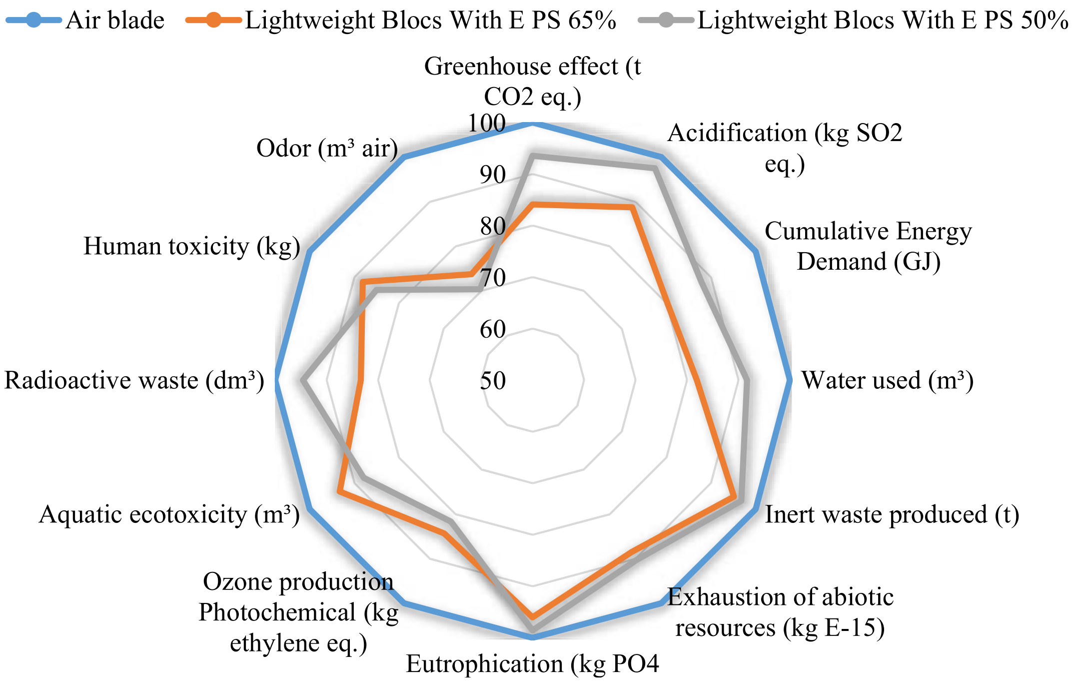


Figure 4. 19: Radar Diagram of exterior walls insulated with: air blade, LWS With 50% of EPS beads and LWS With 65% of EPS beads.

It can also be observed that the low TC of the LWS samples, which are 0.229 w/m.k and 0.197 w/m.k for the content (50% and 65%) of EPS beads, respectively, compared to the TC of hollow clay bricks with 8 and 12 holes of 0.617 w/m.k. and 0.505 w/m.k, respectively, reflect the low operational strength of the building. As explained by Laborel Prenirone et al.[11], the use of materials with low TC can reduce energy requirements for heating and cooling in buildings. Additionally, according to Sheng et al. [171], TC has an impact on energy consumption and environmental emissions for the life cycle of buildings. The life cycle of steel and concrete office buildings built in China was investigated. It was found that the energy consumption and environmental emissions of the life cycle of steel-framed buildings were larger than those of concrete structures. This is due to the higher TC of steel compared to concrete.

According to the findings of these case studies, operational energy has a major share, accounting for about 80% to 94% of the life cycle energy is the use of buildings, followed by construction energy where 6% to 20% is consumed in the extraction, transportation, and production of materials, while the energy of the renovation and demolition process has a negligible share of less than 1% [172].

As for the atmospheric effects, it can be seen that for all the effects, the minimum value is LWS with polystyrene. For example, a similar trend is shown for the impact of greenhouse CO_2. Compared to conventional walls with air blades, it is reduced by estimated values of 6.46% and 15.86% for lightweight walls composed of (50% and 65% EPS beads) respectively. These emissions are mainly due to manufacturing and usage processes. This conclusion too was reported by Pretot et al. [173], who evaluated the influence of thickness and coating on the life cycle of a hemp concrete wall, where it was found that for emissions to atmospheric air, the concrete block had the greatest effect. In contrast, hemp concrete had the lowest impact.

Regarding the effect on water, the value is the lowest for LWS with EPS beads. When comparing the LWS walls with 50% and 65% of EPS beads to conventional walls, the used water dropped by 8.32% and 18.12% for each, which positively influences the environment. In the same context, eutrophication and aquatic environmental toxicity decreased with percentages calculated at 1.48%, 3.98%, and 6.45%, 12.1%, respectively. Similar results were also reported by Kahhat [174], who found that the water pollution index has an impact on the life cycle of residential buildings. Insulated concrete had the lowest environmental impact on water quality, followed by concrete block, cast-in-place concrete, and traditional wood wall systems.

For human health, it can be noted that the traditional wall has the greatest effect, while the LWS wall has the least effect. It was observed that human toxicity effects were reduced by 14.98%and 11.89%. The odor dropped by an estimated value of 29.62% and 26.25% for both 50% and 65% of lightweight walls, respectively, compared with conventional walls.

For the solid waste, the conventional wall does have the biggest effect, while the LWS with 65% has the least one. It was found that the impacts of inert waste produced and radioactive waste are reduced when the walls are more lightweight.
It should be noted that use has the largest emissions of all environmental impacts, followed by the production phase, while the renovation and demolition phases were considered neglected for the other phases. In contrast, there is an exception in the production of inert waste, which has a significant impact on demolition. As depicted in Figure 4.20, Figure 4.21, and Figure 4.22. In this context, Rossi et al. [175] observed that the operational phase accounts for 62% to 98% of the entire life cycle effect, whereas the building phase accounts for 1 to 20% and the decommissioning phase from 0.2% to 5%. Furthermore, Ramesh et al. [2] offered an analysis of 73 research from 13 countries, encompassing residential and commercial structures. They

concluded that the operating phase effects account for 80-90% of the impact, while combined effects account for just 10-20%.

Table 4. 6: Wall insulated with an Air blade

Impact	Construction	Use	Renovation	Demolition	Total
Greenhouse Effect (t CO2 eq.)	96.70	599.53	-1.06	2.04	697.21
Acidification (kg SO2 eq.)	402.48	2 193.11	0.56	23.36	2 619.51
Cumulative Energy Demand (GJ)	1 362.94	25 507.56	16.97	33.41	26 920.88
Water Used (m³)	652.81	45 150.80	1.90	15. 67	45 821.18
Inert Waste Produced (t)	27.22	76.10	0.09	373.17	476.58
Exhaustion of abiotic Resources (kg E-15)	0.34	10.86	0	0.02	11.22
Eutrophication (kg PO4 eq.)	42.92	808.14	0.09	3.65	854.80
Photochemical Ozone production (kg ethylene eq.)	253.21	1 111.43	0.43	25.39	1 390.97
Aquatic Eco-Toxicity (m³)	971 393.98	13 876 704.75	1 043.64	67 119.61	14 916 261.98
Radioactive Waste (dm³)	2.30	50.72	0.03	0.13	53.18
Human Toxicity (kg)	573.42	2 809.22	2.36	28.08	3 413.08
Odor (Mm³ air)	365.96	6 202.08	0.04	2.29	6 570.37

Table 4. 7: LWS with 50% of EPS beads

Impact	Construction	Use	Renovation	Demolition	Total
Greenhouse Effect (t CO2 eq.)	92.54	558.74	-1.06	1.96	652.19
Acidification (kg SO2 eq.)	383.15	2 148.35	0.54	22.35	2 554.39
Cumulative Energy Demand (GJ)	1 132.54	22 484.78	16.24	32.11	23 665.67
Water Used (m³)	624.76	41 367.55	1.84	15.20	42 009.35
Inert Waste Produced (t)	26.13	89.20	1.02	345.00	461.32
Exhaustion of abiotic Resources (kg E-15)	0.33	9.78	0	0.02	10.13
Eutrophication (kg PO4 eq.)	42.09	797.04	0.09	3.50	842.72

Photochemical Ozone production (kg ethylene eq.)	226.30	885.33	0.43	24.29	1 136.24
Aquatic Eco-Toxicity (m³)	843 408.61	12 206 291.95	998.66	60 226.54	13 110 925.76
Radioactive Waste (dm³)	2.20	47.97	0.02	0.12	50.31
Human Toxicity (kg)	548.70	2 232.84	2.27	26.87	2 901.68
Odor (Mm³ air)	350.19	4 272.73	0.04	2.19	4 624.05

Table 4. 8: LWS with 65% of EPS beads

Impact	Construction	Use	Renovation	Demolition	Total
Greenhouse effect (t CO2 eq.)	83.37	502.47	-0.96	1.76	586.65
Acidification (kg SO2 eq.)	346.98	1,956.59	0.48	20.14	2,324.18
Cumulative Energy Demand (GJ)	1,002.54	20,539.14	14.63	28.81	21,585.12
Water used (m³)	562.84	36,941.85	1.64	13.51	37,519.84
Inert waste produced (t)	24.33	85.77	0.08	343.25	453.43
Exhaustion of abiotic resources (kg E-15)	0.29	9.63	0	0.01	9.93
Eutrophication (kg PO4 eq.)	37.92	779.66	0.08	3.15	820.81
Photochemical ozone production (kg ethylene eq.)	218.29	933.02	0.37	21.89	1,173.57
Aquatic eco-toxicity (m³)	837,408.61	13 012 744.12	899.69	57,861.74	13 908 914.16
Radioactive waste (dm³)	1.99	42.24	0.02	0.11	44.35
Human toxicity (kg)	494.33	2,486.80	2.05	24.21	3 007.39
Odor (Mm³ air)	315.49	4,528.09	0.03	1.98	4,845.60

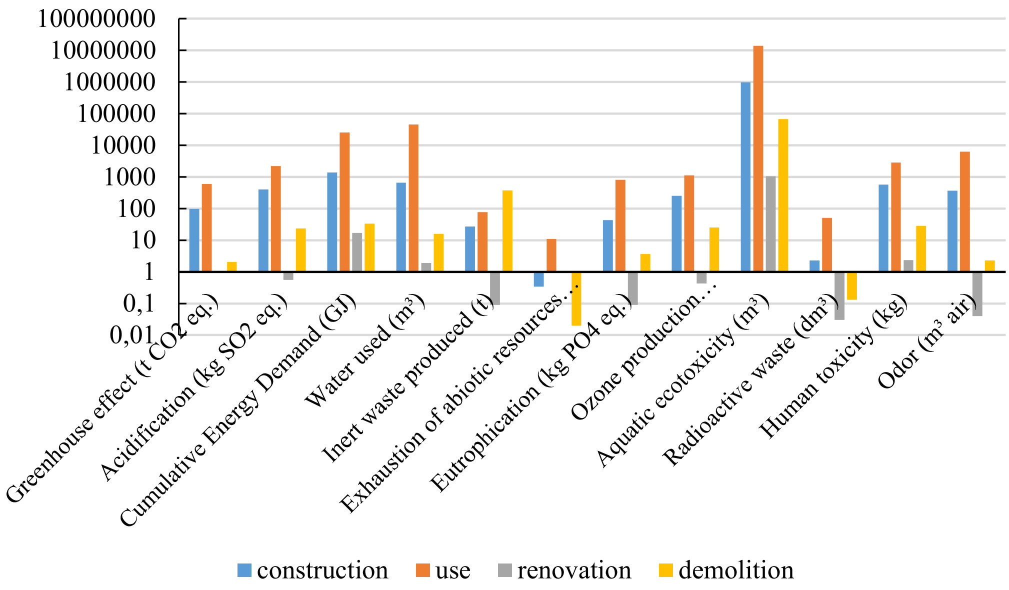


Figure 4. 20: Environmental Impacts of a Wall Insulated with Air Blade by Life Cycle Phase

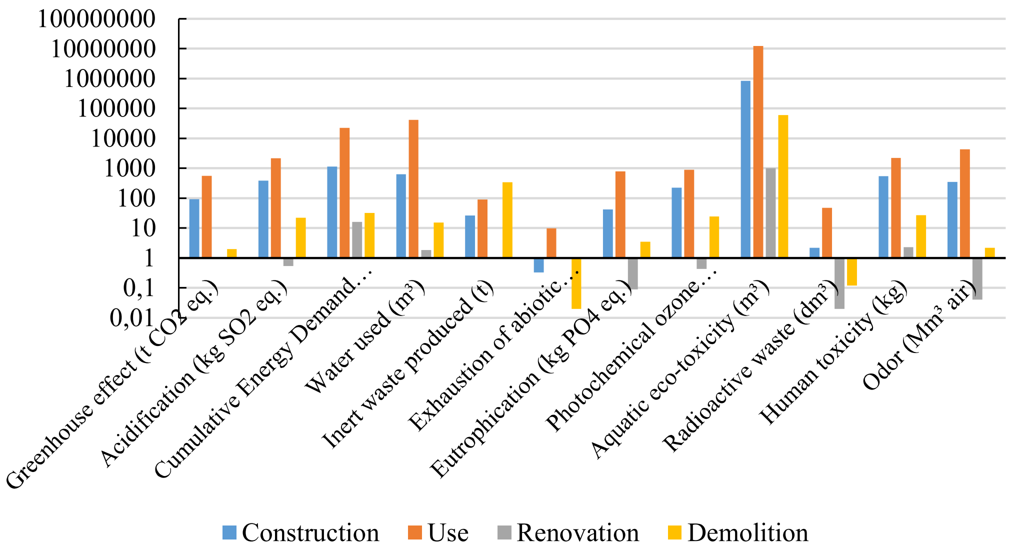


Figure 4. 21: Environmental Impacts of LWS with 50% of EPS beads by Life Cycle Phase

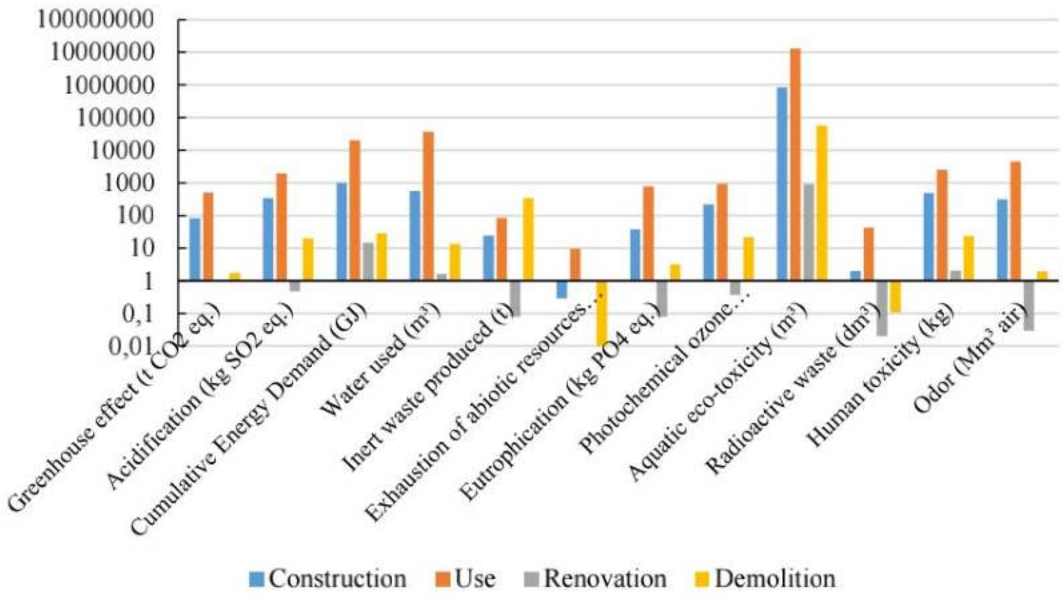


Figure 4. 22: Environmental Impacts of LWS with 65% of EPS beads by Life Cycle Phase

4.3- Effect of the incorporation of natural aggregats into earthen samples

4.3.1- Effect of percentage and sizes of DPW content on the physical properties of lightweight samples

4.3.1.1- The apparent density

Figure 4.23 demonstrates the variation of apparent density of LWS as a function of the percentage of DPW and sizes. In general, the samples with the lowest percentage of date palm waste had the highest density of three sizes. The bulk density of LWS samples incorporating DPW <1 mm, DPW (1–5) mm, and DPW (5-10) mm decreased by about 34.72%, 36.32%, and 37.94%, respectively, with the increase in the amount of date palm waste from 0% to 75% in the mixture. The same trends reported by Benmansour et al. [176] found that the incorporation of date palm fibers (DPF) in the ciment mortar decreases the density and increases the insulating capacity of mortar by decreasing its thermal conductivity.

This decrease is due to the lower apparent density of DPW< 1mm, DPW (1–5) mm, and DPW (5-10) mm, estimated at 133 kg/m^3, 109 kg/m^3, and 103 kg/m^3, respectively, as compared to that of the mixture (soil + quicklime), which is equal to 1505.43 kg/m^3. Laborel et al [110]. Demonstrate in the same context that the lower bulk density of mixtures may be a result of the lower bulk density of particles.

This reduction is also the consequence of the soil samples' increased porosity, which occurred as a result of the DPW being saturated with water within 24 hours of being used. This caused the water to evaporate during the drying process of the made earth samples, increasing their porosity, and it also caused the DPW particles to detach from the matrix soil after shrinkage, expanding the material's porous network [12].

Moreover, it is observed that when the DPW is large, the samples are lighter. This is because DPW (5-10)mm had a larger particle size, which resulted in more gaps between the DPW and the soil matrix, and DPW had smaller particle dimensions, resulting in a more homogeneous end product, with fewer pores and higher density [177]. The same results were reported by Masri et al. [178] , who carried out an experimental study on an innovative wood-plastic (WPC) material based on date palm and expanded polystyrene waste (EPS). The results showed that the material is lighter when the reinforcement size is large.

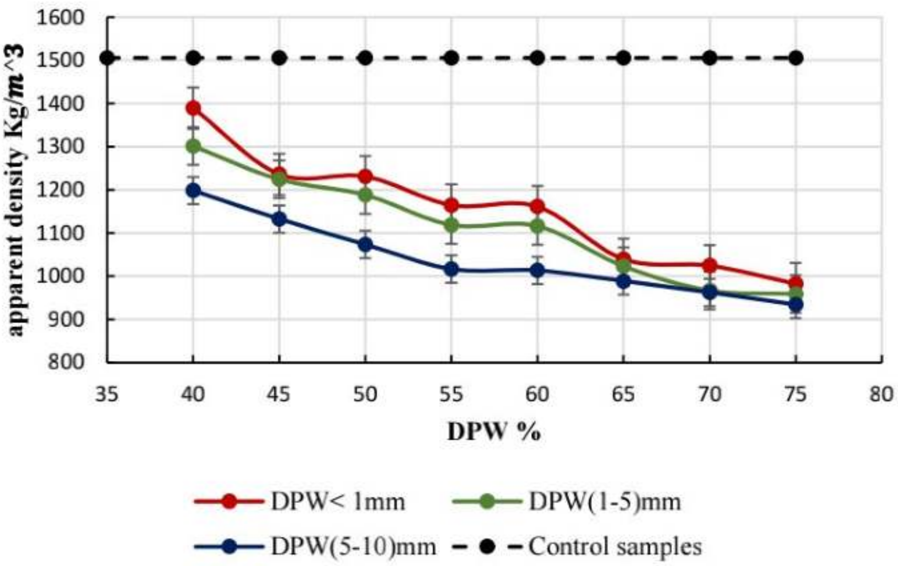


Figure 4. 23: variation of apparent density of LWS as a function of the percentage and sizes of DPW.

4.3.1.2- Ultrasonic pulse velocity (UPV)

Figure 4.24 show the variation of content ratio (DPW) and sizes on the propagation speed of ultrasonic waves of LWS. It was observed that when the amount of DPW in the matrix (soil and lime) increased, the wave propagation velocity declined significantly for three sizes, with an estimated value of 53.90%, 61.33%, and 64.68% for samples containing 75% of DPW <1 mm, DPW(1–5) mm, and DPW(5-10) mm, respectively, compared with reference samples (0% DPW) corresponding to the ultrasonic pulse velocity of 1345 m/s. Thus, the wave propagation speed is low when the size of the content is large. This decrease in ultrasound pulses between samples with DPW <1 mm, DPW (1–5) mm, and DPW(5-10)mm can be explained by the difference in the size of the DPW content. DPW (5-10) mm had a larger particle size, which resulted in more gaps between the DPW and the matrix (soil and lime), but DPW <1 mm had smaller particle dimensions, resulting in a more homogeneous final product with fewer particles and pores (the speed of propagation of waves in air is lower than the speed of propagation of solids). This decrease is also due to the higher sound insulation coefficient of plant aggregates compared to earth concrete or cement concrete.

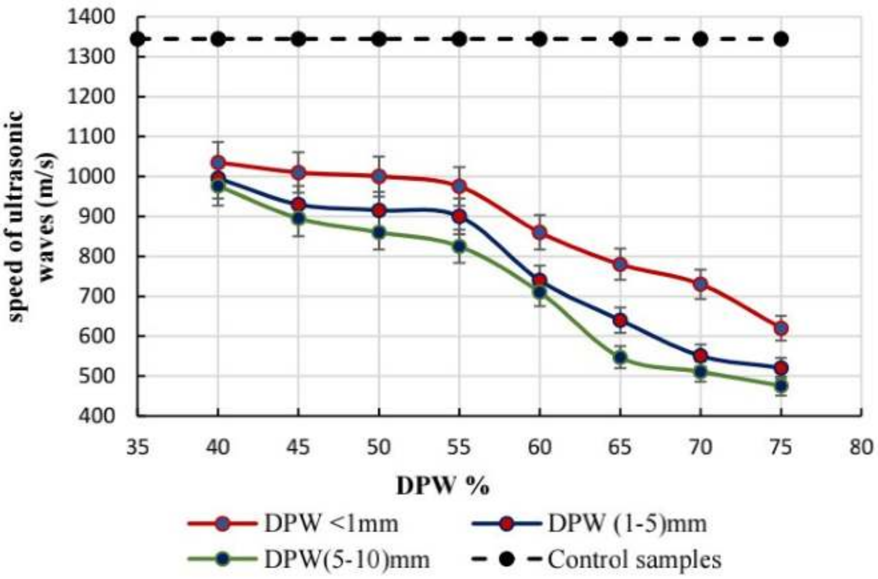


Figure 4. 24: variation of propagation speed of ultrasonic waves of LWS as a function of the percentage and sizes of DPW.

4.3.2- Effect of percentage and sizes of DPW content on the thermal properties of lightweight samples

4.3.2.1- Thermal conductivity

Figure 4.25 shows the variation of thermal conductivity as a function of the percentage and sizes of DPW. From this result, it can be seen that the incorporation of DPW into the soil mixture leads to an increase in the thermal insulation performance of the earth samples, with an estimated value of 49.35%, 51.52%, and 54.83% for samples containing 75% of DPW <1 mm, DPW (1–5)mm, and DPW(5-10)mm, respectively, compared with reference samples (0% DPW), corresponding to a thermal conductivity of 0.462 W/m.K. This decrease is expected because DPW has a lower thermal conductivity than the soil matrix, which was found equal to

0.0738 (W/m.K)[12]. On the other hand, the variation in thermal conductivity is due to the voids that are created when increasing the percentages and sizes of the DPW and to the poor adhesion between the binder and DPW, as shown in Figure 4.25. According to [23, 176], the presence of fibers in the matrix creates voids, which leads to an increase in porosity and a decrease in density.

In general, the thermal conductivity of LWS decreases by increasing the percentage and size of DPW. The same results have been found by Masri et al. [178], who discovered that reducing the size and amount of reinforcement increases thermal conductivity. Similar behavior of thermal conductivity was reported by Chicki et al. [179] using the same fiber (DPF). It was found that the thermal conductivity of gypsum composites filled with 10% of DPF3 (3mm) and DPF6 (6mm) is 62% and 66% lower than that of neat gypsum, respectively. It is concluded that the effect of DPF size on thermal properties is less clear than that of DPF concentration. Additionally, Labouda et al. [180] found that the percentage and length of Typha australis fibers in reinforced clay have an effect on the bulk density and thermal conductivity. Increasing the length and percentage of fibers decreased the bulk density of the composite, which led to a decrease in the thermal conductivity. When the percentage ranges from 0 to 55%, the thermal conductivity decreases from 1.03 to 0.146 W/mK and from 1.03 to 0.113 W/mK for each of the fiber lengths of 1 cm and 3 cm, respectively. According to Al Rim et al. [100], when the percentage of wood aggregates increases from 10% to 50%, the thermal conductivity of clay-cement composites drops from 0.24 to 0.08 W/mK. Olacia et al. [181] found that incorporating higher percentages and longer lengths of fiber content (seagrass fibers and straw) into clay bricks led to a decrease in density and consequently improved thermal conductivity.

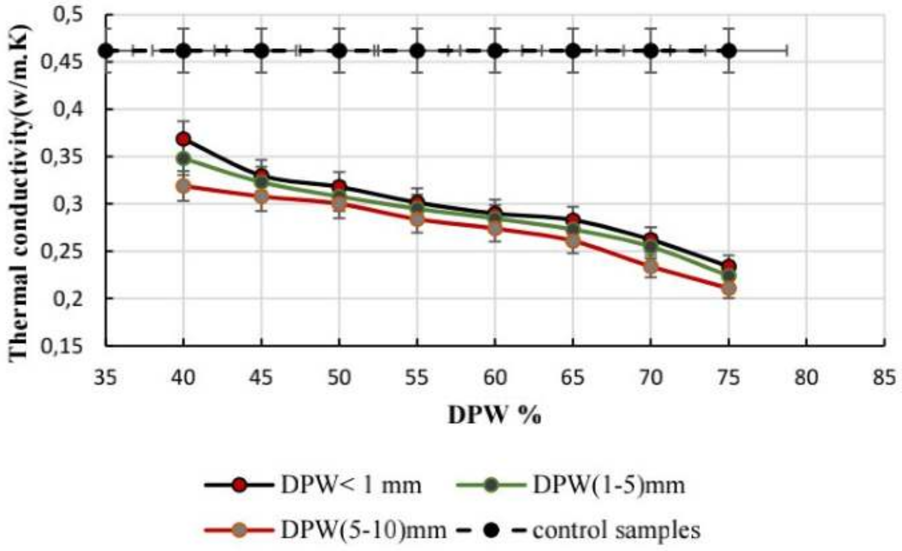


Figure 4. 25: variation of thermal conductivity as a function of the percentage and sizes of DPW of LWS.

4.3.2.2- The Specific heat capacity

The specific heat defines a material's ability to store energy: it is the heat required by 1 kg of material to modify its temperature of 1 K, and it is calculated in J/kg K [7]. Figure 4.26 depicts the variation of specific heat as a function of the percentage and size of the DPW of LWS. Indeed, the specific heat dropped as the DPW content increased ; the specific heat values ranged from 1477 J/kg.k (0% DPW) to 1369.4 J/kg.k ,1236.5 J/kg.k, and 1201.3 J/kg.k (40% DPW) to 984.2 J/kg.k, 935.4 J/kg.k, and 929.4 J/kg.k (75% DPW) for DPW <1 mm, DPW (1–5) mm, and DPW(5-10)mm, respectively, which corresponds to an abatement of about 33.36% , 36.67%, and 37.08% compared with the reference block. This decline is attributed to the fact that the density and volumetric heat capacity of LWS decreased, so specific heat decreased too. Similar results were obtained by Atiki et al.[97].

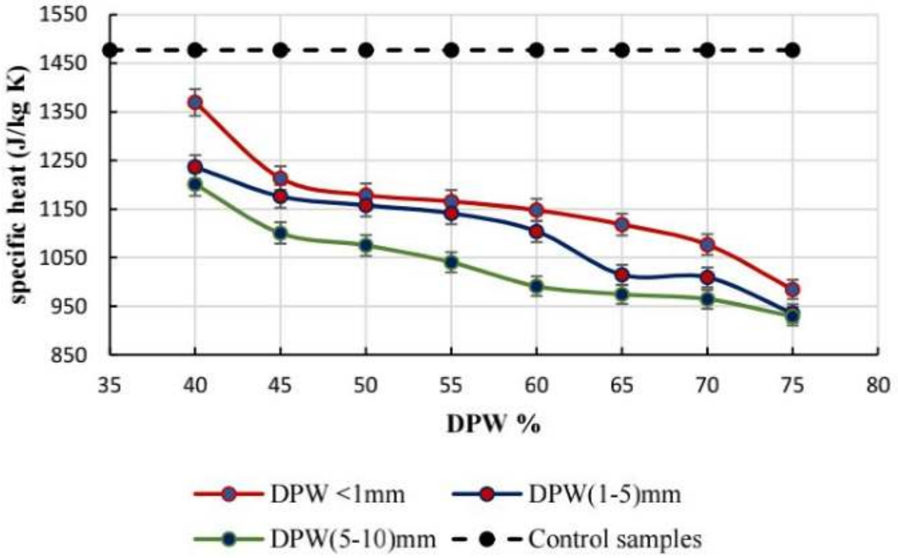


Figure 4. 26: variation of specific heat as a function of the percentage and sizes of DPW of LWS

4.3.2.3- Thermal effusivity

Thermal effusivity is the material's ability to exchange energy with its surroundings, which is defined as the square root of the product of thermal conductivity and energy storage [163]. Figure 4.27. Depicts the variation of thermal effusivity as a function of DPW percentage and size. It can be seen that the thermal effusivity of LWS decreases as the size and content of DPW increase. This decrease is about 53.06%, 55.78%, and 57.77% for samples containing 75% of DPW <1 mm, DPW (1–5) mm, and DPW (5-10)mm, respectively, compared with reference samples (0% DPW), corresponding to a thermal effusivity of 1013.54 J. $s^{-1/2}.m^{-2}.K^{-1}$. Additionally, it decreased by an estimated 17.38%, 26.17%, and 33.14% for samples containing 40% of DPW <1 mm, DPW (1–5) mm, and DPW (5-10)mm, respectively, compared with reference samples. As a result, LWS have a lower ability to exchange heat with their environment than reference samples. Similar findings were reported by Djoudi et al. [107], who investigated the effect of length and fiber content on the thermal and physical properties of gypsum reinforcement with a DPF mesh and found that the thermal effusivity decreased when increasing the length and percentage of date palm fibers.

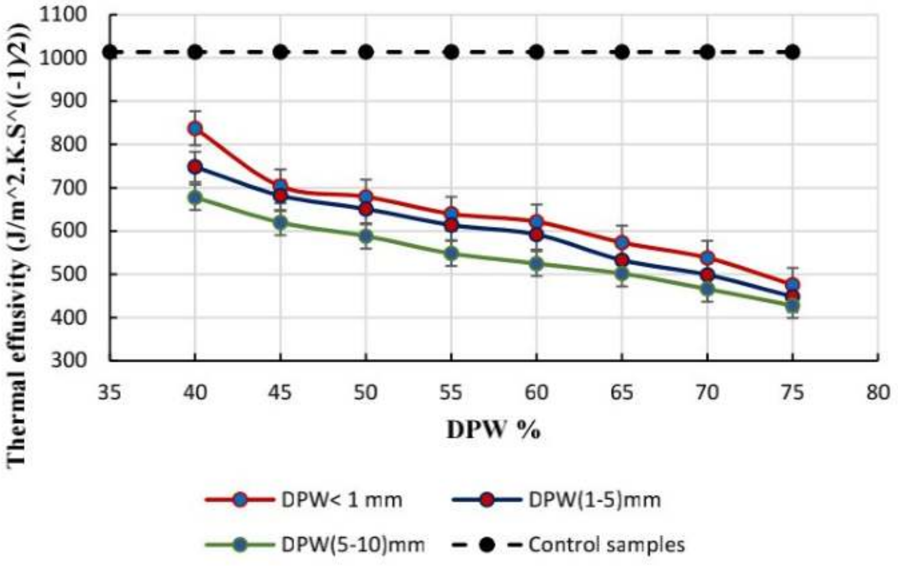


Figure 4. 27: variation of thermal effusivity as a function of the percentage and sizes of DPW of LWS

4.3.2.4- Volumetric heat capacity

The volumetric thermal capacity, q.Cp, is a significant characteristic for determining the thermal inertia of building materials and was calculated using the relationship « 3.3 » [162]. Figure 4.28 presents the variation of volumetric heat capacity as a function of the percentage and sizes of DPW of LWS. It can be seen that the volumetric capacity is reduced by up to 56.50%, 59.67%, and 60.95% for 75% content for the three sizes DPW < 1 mm, DPW (1–5) mm, and DPW(5-10)mm, respectively, compared to the reference samples (0% DPW), corresponding to the volumetric capacity of 2.223 $Mj/m^3.K$. This decrease is attributed to the lower volumetric heat capacity of DPF, which is 234 $kJ.m^{-3}.K^{-1}$ compared to the reference samples This reduction notably affects the heat capacity of the composite material, as highlighted by Boumhaout et al.[162]. Similar findings were reported by Charai et al [182], who examined the influence of incorporating Moroccan hemp fibers on the thermal performance of gypsum. The study revealed a 24.8% decrease in volumetric heat capacity when compared to gypsum without additives.

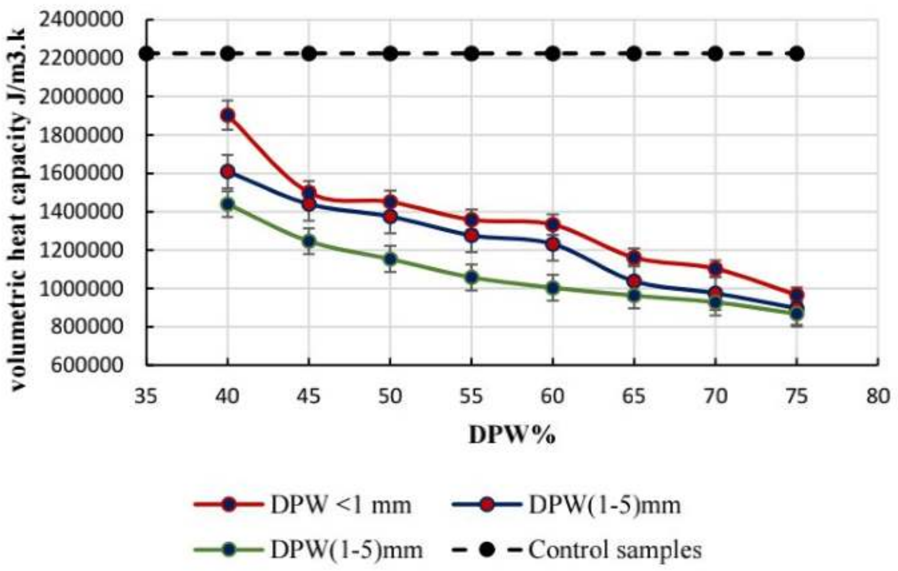


Figure 4. 28: variation of volumetric heat capacity as a function of the percentage and sizes of DPW of LWS

4.3.3- Effect of percentage and sizes of DPW content on the mechanical behavior of earthen samples

4.3.3.1- dry compressive strength

The mechanical behaviour of LWS incorporating DPW is presented in Figures 4.29, 4.30, and 4.31. Ultimate strain, and elastic modulus for all samples are shown in Tables 4.9, 4.10 and 4.11.

It was observed that for samples containing 40% to 60% of the two sizes of DPW<1mm and DPW (1-5) mm and 40% to 55% of DPW (5-10) mm, the mechanical behavior can be divided into two phases. The first phase showed a near-linear behavior until the maximum stress was reached, and the second phase showed a negative slope ranging from steep to flat with increasing DPW content. For samples containing 65% to 75% of both sizes of DPW<1mm and DPW (1-5) mm and 60% to 75% of DPW (5-10) mm, compression does not lead to the failure of samples. In other words, deformation does not lead to fracture of the compressed samples but rather to a continuous increase in stress, which is attributed to the porous material's irreversible compaction [183]. It is also noted that the quantity of fiber impacts the compressive characteristics of the composite. This behavior is similar to that observed for the date palm fibers and lime compound with Belakroum [184].

From Figures 4.29, 4.30, and 4.31, it can be observed that the value of the curves decreases with the increase in the particle size of the DPW contains, and the samples become more ductile compared to the samples that contain a small DPW size (DPW<1mm). A similar result was obtained by Chikhi et al. [179], who studied the influence of two different sizes of DPF (3 and 6 mm) on the mechanical characteristics of gypsum-based materials. Who discovered that the DPF3-based gypsum materials present higher compressive and flexural strengths than the materials filled with larger particles (DPF6).

It should also be noted that the lowest compressive strengths were achieved with the highest percentage of DPW content for three sizes (DPW < 1mm, DPW (1-5)mm, and DPW (5-10) mm) as shown in Figure 4.23, and the results from 40% to 45% met the standard requirement for compressive strength for three sizes (The minimum strength of unfired clay bricks is 1 MPa) [165, 177, 185].

According to the Tables 4.9, 4.10, and 4.11, the compressive strength decreases as the percentage of DPW increases. Estimated at 96.70%, 97.39%, and 97.79% for samples containing 75% of DPW <1mm, DPW (1–5) mm, and DPW (5-10) mm, respectively, compared with reference samples. Furthermore, the mechanical performance of the compressive strength decreases with the increase of the contain ratio from 40% to 75%, as indicated by the estimated values of 71.13%, 73.44%, and 75.76% for DPW<1mm, DPW (1-5)mm, and DPW(5-10)mm, respectively. This decline is expected due to the weak compressive strength and stiffness of DPW. And also due the weak adhesion between DPW and matrix, as indicated by Taallah et al [92]. This decrease is also attributed to an increase in the pores caused by increasing the percentage and size of DPF in the samples. According to Kjoudja et al.[12], a decrease in compressive strength is due to the heterogeneous microstructure. This is because the pore sizes become larger and larger due to the interlocking caused by the date palm aggregates, which are generally found in different shapes and sizes. As illustrated in Figure 4.35 (a, b, and c).

It is worth noting that the modulus of elasticity of LWS as a function of percentage and size of DPW content ranges from 388.82 MPa for the control sample, which exhibits significant rigidity (block burst), to 24.98 MPa, 19.27 MPa, and 16.926 MPa for samples containing 75% of DPW< 1 mm, DPW (1–5 mm), and DPW (5-10)mm, respectively, which exhibit ductile damage, as shown in Tables 4.9, 4.10, 4.11, and Figures 4.29, 4.30, and 4.31. This contrast in behavior reflects the great ductility of the composite material after the addition of the date palm waste [12]. It can also be seen that the modulus of elasticity decreases when the DPW is increased for three sizes and decreases by an estimated 93.57%, 94.89%, and 95.65% for DPW

<1 mm, DPW(1-5) mm, DPW(5-10)mm, respectively, compared to the reference samples, as shown in Figure 4.34.

The results of the stress-strain curves showed an increase in the elastic performance of the DPW-containing samples, which have a high ultimate strain. The corresponding values ranged from 3.14 mm for the control sample (0% DPW) to 14 mm for the samples that contained 75% DPW for the three sizes. These results highlight the ductile of samples to failure, as samples with a content of 40% to 60% for DPW <1mm and DPW(1-5)mm, and samples with a content of 40% to 55% for DPW (5-10) mm, show a high plastic phase and have underwent displacement before fracture, whereas samples with contents of 65% to 75% for two sizes of DPW < 1mm and DPW(1-5) mm and 60% to 75% of DPW(5-10)mm, respectively, the compression of the samples does not lead to their failure, but leads to a continuous increase in the ultimate strain and in the pressure without breaking the compressed samples.

Table 4. 9: Compressive strength of earthen samples incorporating DPW <1mm.

DPW <1mm %	compressive strenght MPa	Moludus of elasticity (MPa)	Ultimate deflection (mm)
0	12.42	388.82	3.14
40	1,420	122.08	3,72
45	1,230	105.25	4,98
50	0,940	86.211	3,26
55	0,830	64,236	4,23
60	0,789	57,149	6,87
65	0,50	44,805	14
70	0,47	34.168	-
75	0,41	24.98	-

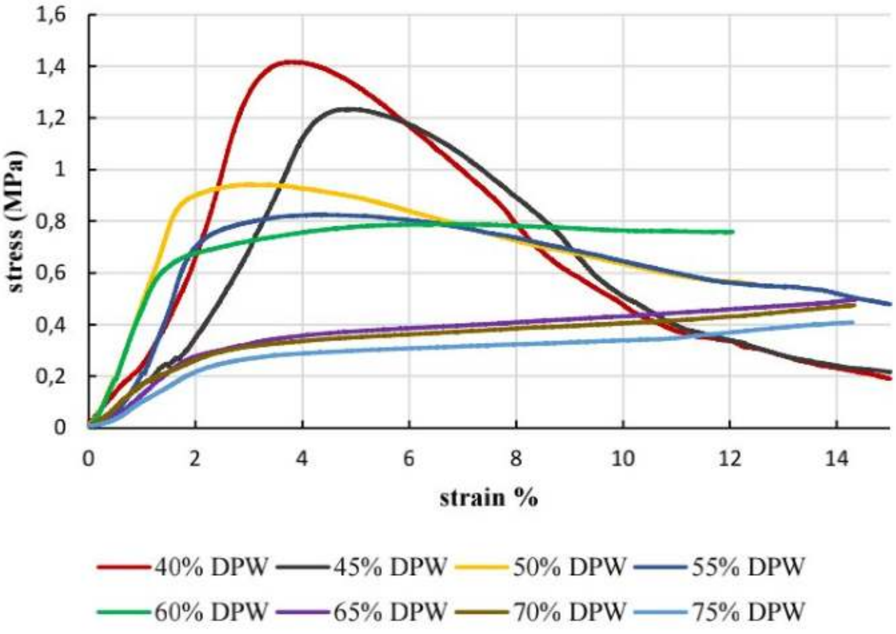


Figure 4. 29: Mechanical behaviour of the compressive tests of earth samples incorporating DPW <1mm.

Table 4. 10: Compressive strength of earthen samples incorporating DPW (1-5) mm.

DPW (1-5)mm %	Compressive strenght Mpa	Modulus of elasticity (MPa)	Ultimate strain (mm)
40	1,222	81.1	2,61
45	1,137	78.207	2,87
50	0,920	68.865	3,17
55	0,72	60.036	3,62
60	0,663	51.504	6.07
65	0,44	39.18	-
70	0,36	25.379	-
75	0,324	19.870	-

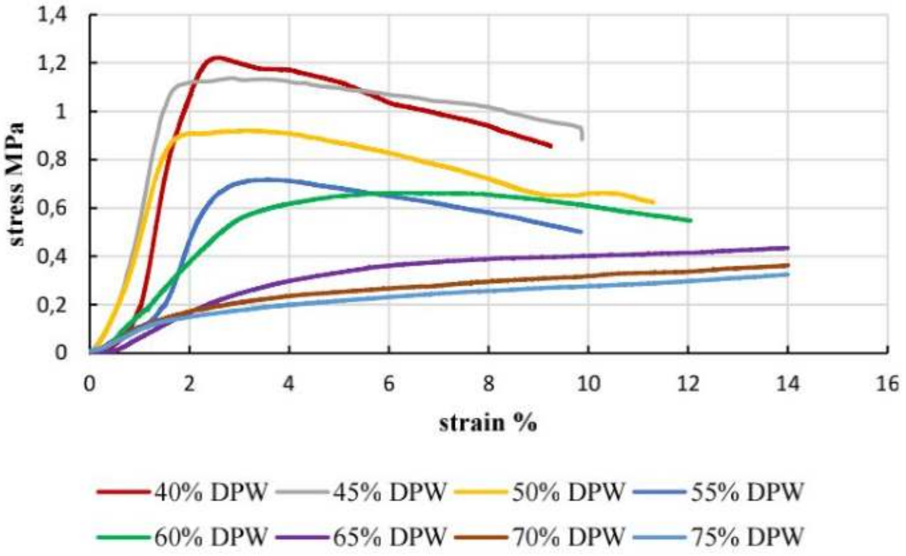


Figure 4. 30: Mechanical behaviour of the compressive tests of earthen samples incorporating DPW(1-5) mm.

Table 4. 11: Compressive strength of earthen samples incorporating DPW (5-10) mm.

DPW (5-10) mm	Compressive strenght Mpa	Modulus of elasticity (MPa)	Ultimate strain (mm)
40%	1.126	82.405	3.18
45%	1.00	79.630	3.554
50%	0.817	63.046	5.668
55%	0.715	57.394	11.705
60%	0.511	47.519	-
65%	0.428	34.333	-
70%	0.350	22.143	-
75%	0.274	16.926	-

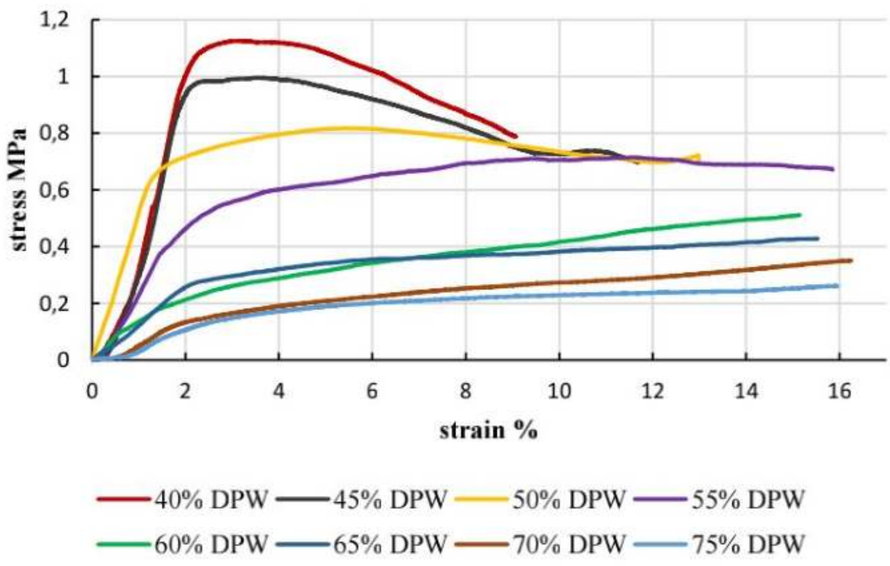


Figure 4. 31: Mechanical behaviour of the compressive tests of earthen samples incorporating DPW (5-10) mm.

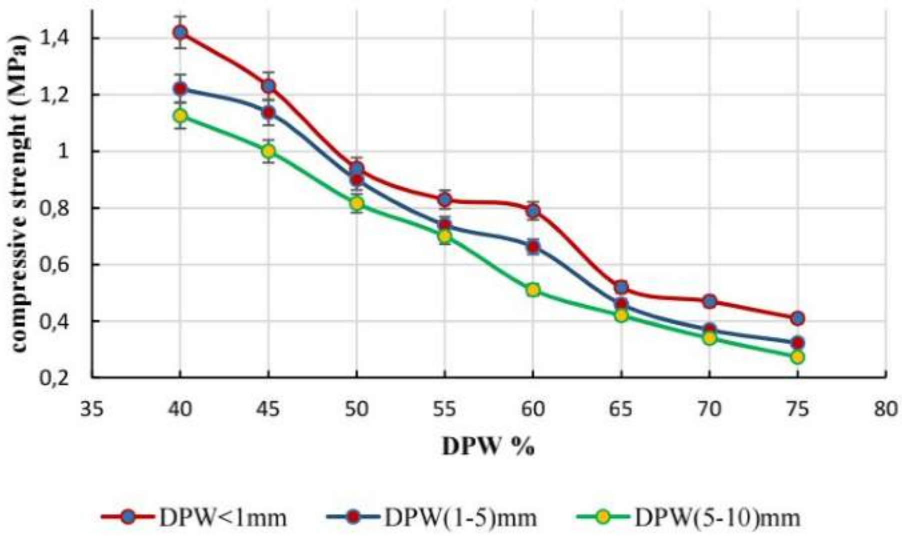


Figure 4. 32: Compressive strength of LWS as a function of percentage and sizes of DPW content.

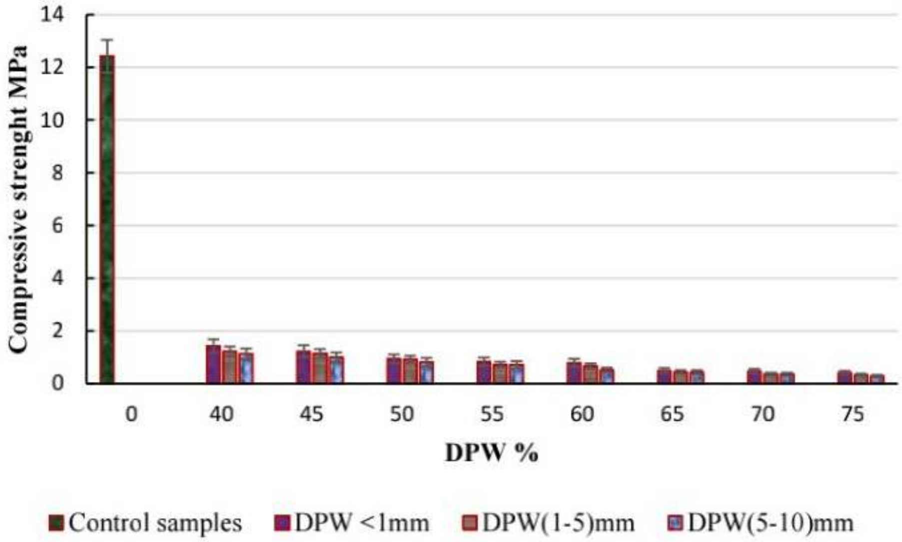


Figure 4. 33: The compressive strength of LWS compared with reference samples

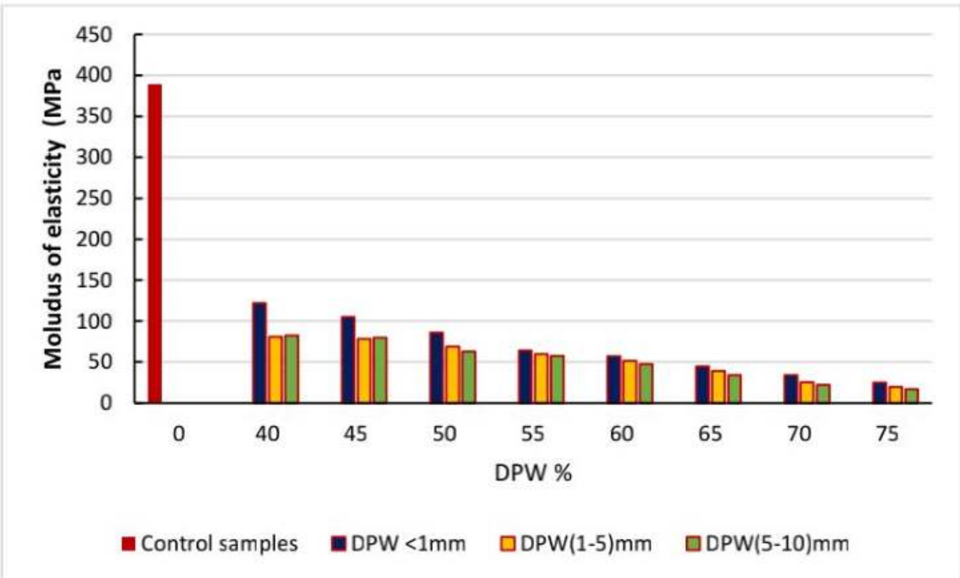


Figure 4. 34: Modulus of elasticity of LWS as a function of percentage and sizes of DPW content.

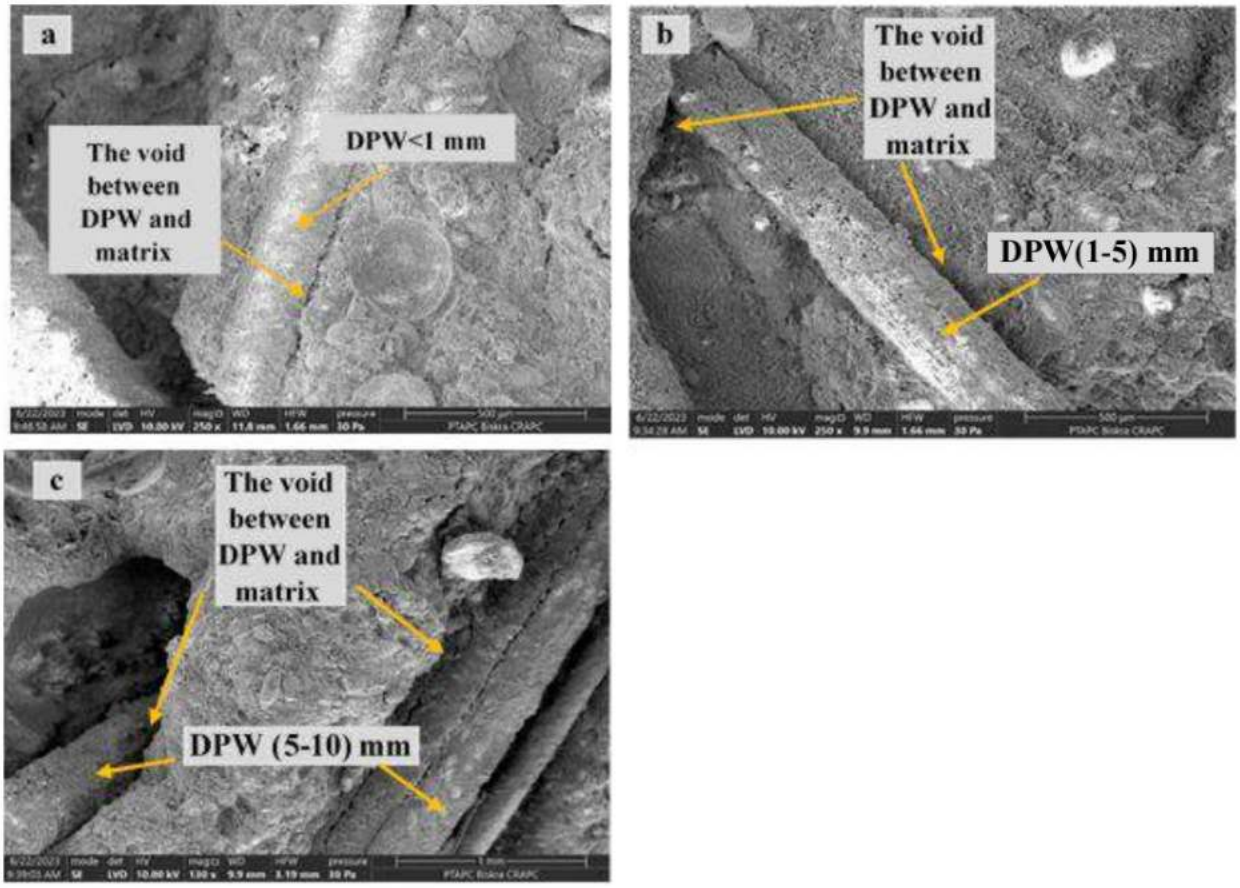


Figure 4. 35: SEM images of samples: (a) With DPW<1mm, (b) With DPW (1-5)mm), (c) With DPW(5-10)mm.

4.3.3.2- Flexural behaviour

The effect of the contain ratio (DPW) and sizes on the load deflection curves of the three-point flexural test for earth samples are presented in Figures 4.36, 4.37, and 4.38. The corresponding parameter values are summarized in Tables 4.12, 4.13, and 4.14.

From Figures 4.36, 4.37, and 4.38, it can be observed that the value of the curves decreases with the increase in the particle size of the DPW contained. However, there was a corresponding improvement in the ductility of the samples. Furthermore, the reference samples show a brittle failure as shown in Figure 4.15. Additionally, it should be noted that the two parts of the sample containing DPW did not break apart instantly for the three sizes because the date palm waste present in the soil matrix prevented the possibility of brittle fracture, as depicted in Figure 4.41. It should also be noted that the mechanical performance of the three-point bending strength decreases with the increase of the contain ratio and the samples become more plastic due to the DPW content, which enhances the sample plasticity and delays the breaking of the composite material [162]. Figure 4.39 shows the reduction in flexural strength of earth samples as a function of DPW content by an estimated value of 92.09%, 94.35%, and 95.81% for samples containing 75% of DPW <1mm, DPW(1-5) mm, and DPW(5-10)mm, respectively, compared with reference samples. Several studies have found a similar trend [12, 97, 162, 176, 177] that the higher the fiber content in the mixture, the lower the mechanical performance of the three-point bending strength of samples. This decrease in strength is attributed to the heterogeneous fiber distribution, larger gaps caused by larger fiber lengths, and lower cohesion between the fibers and the soil matrix[177] as depected in figure 4.35.

Furthermore, samples with contents ranging from 40% to 65% of DPW <1mm and 40% to 45% of both sizes of DPW(1-5)mm and DPW(5-10)mm met the standard bending strength requirements (0.25-0.50 MPa) [177, 186, 187].

Figure 4.40 and tables 4.12, 4.13, and 4.14 show the flexural elastic modulus of LWS as a function of DPW content. It can be noticed that the flexural elastic modulus drops when the percentage of DPW rises for the three sizes by an estimated value of 89.36%, 89.97%, and 90.80% for DPW <1mm, DPW(1-5)mm, and DPW(5-10)mm, respectively, compared with reference samples. It is also observed that the flexural modulus decreases generally with increasing the particle size of the reinforcement, from DPW<1mm to DPW(5-10)mm samples, and the LWS material becomes more ductile. Also, for the ultimate deflection, it can be noted that the presence of DPW confers the material an increase in the ultimate deflection. Through Tables 4.12, 4.13, and 4.14, the results show that the ultimate deflection of samples with content DPW (5-10) mm is greater than that of samples with content DPW <1mm and the reference samples. It can be explained that the crack occurs and propagates directly in the matrix due to the small size of the content. By increasing the size of the content particles from DPW(5-10)mm, the sample acquires ductility and supports the stresses transmitted by the matrix, which delays the fracture of the material [178]. The same results were reported by omrani et al.[98]. It was found that the presence of Juncus acutus fibers in the clay-sand composite confers the material an increase in the ultimate deflection. At maximum load, the deflection ranged from 0.325 mm for the control sample to 0.774 mm for the composite with 20% fibers.

Table 4. 12: Mechanical parameters in flexural of LWS incorporating DPW<1mm.

DPW <1mm %	Load (KN)	Stress (MPa)	Moludus of elasticity (MPa)	Ultimate deflection (mm)
40	0.227	0,533	79.688	0.411
45	0.180	0,423	70.200	0.333
50	0.164	0,384	51.768	0.772
55	0.145	0,340	36.469	0.553
60	0.133	0,311	32.800	0.674
65	0.119	0,278	30.811	0.672
70	0.086	0,203	28.803	0.657
75	0.080	0,189	23.581	0.560

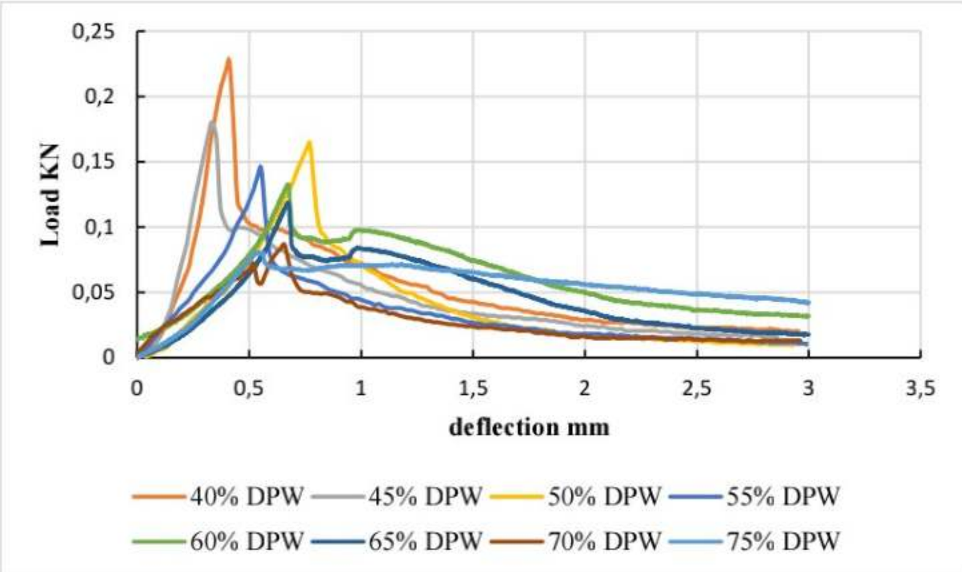


Figure 4. 36: load-deflection curves of the flexural tests of LWS incorporating DPW <1mm

Table 4. 13: Mechanical parameters in flexural of LWS incorporating DPW (1-5)mm.

DPW(1-5)mm %	Load (KN)	Stress (Mpa)	Modulus of elasticity (MPa)	Ultimate deflection (mm)
0	1.020	2.390	221.620	0.406
40	0.204	0,479	74,114	0,313
45	0.158	0,371	63,794	0,444
50	0.101	0,237	46,664	0,591
55	0.096	0,226	34,524	0,432
60	0.078	0,182	31,488	0,629
65	0.068	0,160	27,127	0,728
70	0.065	0,153	24,438	1,112
75	0.058	0,135	22,232	1,335

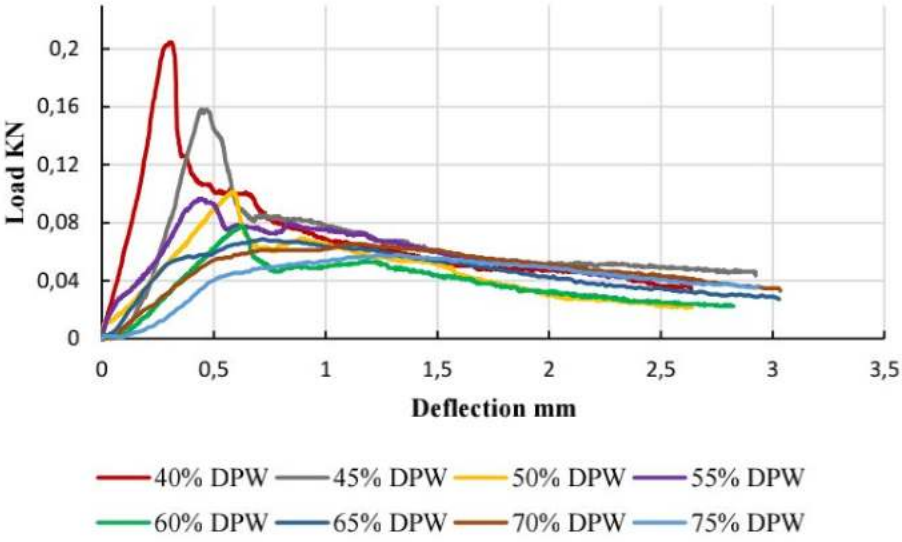


Figure 4. 37: Load-deflection curves of the flexural tests of LWS incorporating DPW (1-5) mm.

Table 4. 14: Mechanical parameters in flexural of LWS incorporating DPW (5-10).

DPW (5-10)mm	Load	Stress	Modulus of elasticity	Ultimate deflection
%	**(KN)**	**(Mpa)**	**(MPa)**	**(mm)**
0	1,02	2,390	221,620	0,406
40	0,158	0,370	70.680	0,444
45	0,135	0,316	61.321	0,3
50	0,1	0,234	43.743	0,896
55	0,085	0,199	31.709	1,048
60	0,073	0,171	30.154	0,98
65	0,067	0,157	25.024	1,017
70	0,058	0,135	22.372	1,25
75	0,043	0,100	20.395	1,505

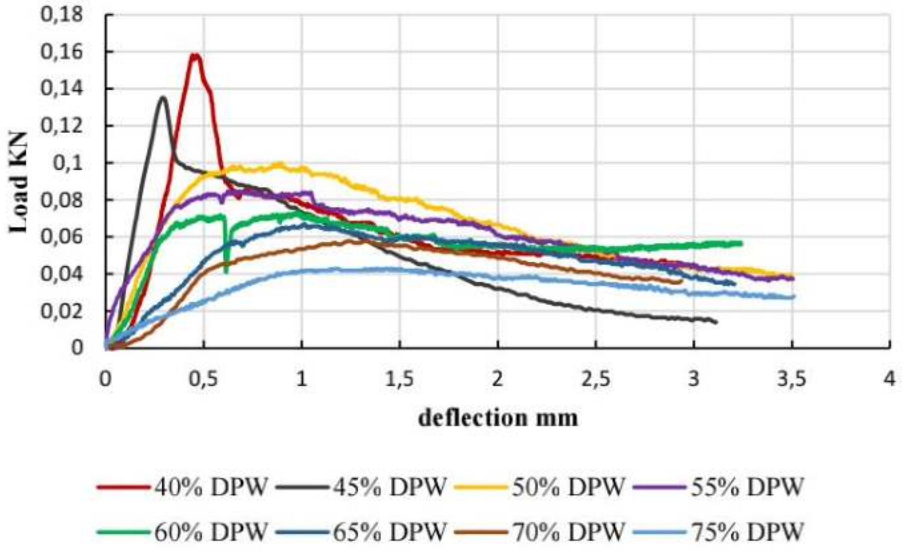


Figure 4. 38: Load-deflection curves of the flexural tests of LWS incorporating DPW (5-10)mm.

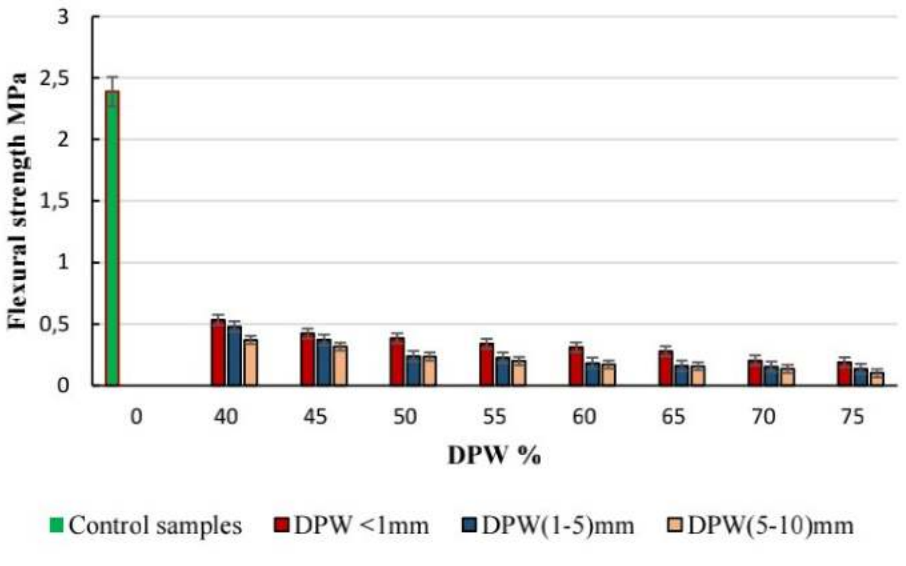


Figure 4. 39: Flexural strength of LWS as a function of percentage and sizes of DPW content

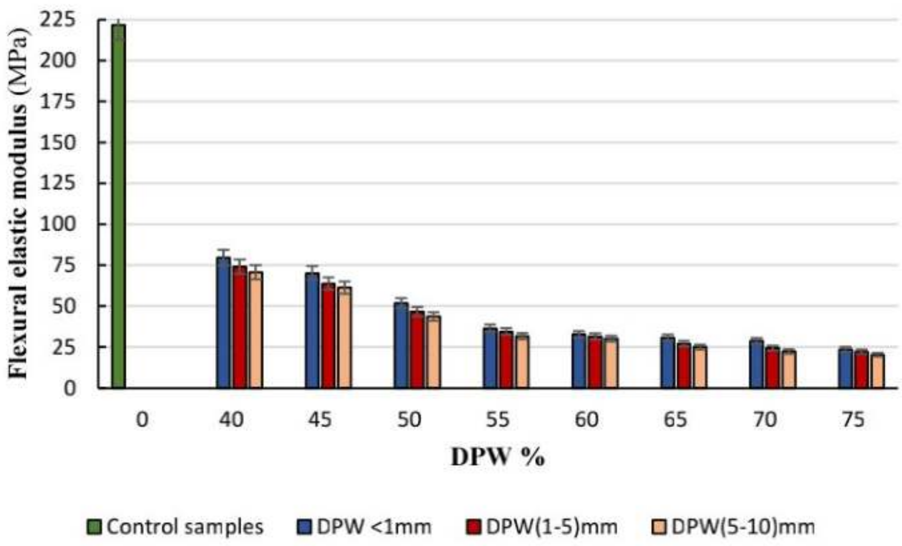


Figure 4. 40: Flexural elastic modulus of earth samples as a function of percentage and sizes of DPW content.

Figure 4. 41: Specimen after failure under flexural test.

4.4- Conclusion

This experimental study investigated the effect of the incorporation of EPS beads and DPW content on raw earth stabilized by quicklime. The physical, mechanical, and thermal properties of the LWS were measured by changing the EPS content from 40% to 65% by volume and the DPW content from 40% to 75% by volume for three different sizes of DPW. The results can be summarized as follows:

- The study revealed a decrease in apparent density of 62.24% for the samples containing 65% EPS beads and a decrease of about 34.72%, 36.32%, and 37.94%, respectively, for samples containing 75% of DPW <1 mm, DPW (1–5) mm, and DPW (5–10) mm, respectively, compared with reference samples (0% DPW).
- An increase in the content of EPS beads and DPW in the lightweight samples led to a reduction in the wave propagation velocity. Samples containing 65% EPS beads and 75% DPW < 1 mm, DPW (1–5) mm, and DPW (5–10) mm showed estimated values of 76.95%, 53.90%, 61.33%, and 64.68%, respectively, compared to the reference samples (0% DPW). Furthermore, the observation revealed a decrease in wave propagation speed correlating with both the size and percentage increase in DPW content.
- The study demonstrated a significant enhancement in the thermal performance of samples upon the addition of EPS beads and three different sizes of DPW. The results revealed an average reduction in thermal conductivity by 57.36%, 49.35%, 51.52%, and 54.83% in samples containing 65% EPS beads and 75% of DPW <1 mm, DPW (1–5) mm, and DPW (5–10) mm, respectively, compared to the reference samples (0% DPW). These improvements were notably observed in comparison to the reference samples.
- Increasing the percentage of EPS beads and the percentage and size of DPW in the LWS formulation resulted in a decrease in thermal effusivity. This decrease is about 75.5%, 53.06%, 55.78%, and 57.77% for the samples containing 65% EPS beads, 75% of DPW < 1 mm, DPW (1–5) mm, and DPW (5–10) mm, respectively, compared to the reference samples (0% DPW), which indicates that the LWS has lower heat exchange capabilities with its environment compared to the reference samples. Furthermore, volumetric heat capacity and specific heat decreased as the EPS beads content and the percentage and size of DPW increased.
- Moreover, the results of the study revealed that as the percentage of EPS beads and the percentage and size of DPW increased, the mechanical performance of the LWS

declined. However, there was a corresponding improvement in the ductility of the samples. It is worth mentioning that the samples containing 40–50% EPS beads and those with 40% to 45% DPW for three different sizes, as well as the reference bricks, were found to be in compliance with Turkish standards for load-bearing walls. On the other hand, the remaining samples are suitable for use in insulating walls.

- The study indicated a substantial decrease in the modulus of elasticity with an increase in the EPS content, percentage, and size of DPW.
- The addition of EPS beads and three sizes of DPW increases the ductility of raw earth bricks and also increases the energy absorption capacity under compressive load. In addition, it was found that for specimens containing 65% to 75% of both DPW<1 mm and DPW (1–5) mm and 60% to 75% of DPW (5–10) mm, compression does not lead to failure of the specimens; rather, it leads to a continuous increase in stress.
- The SEM microstructure analysis revealed good adhesion between the EPS beads and the matrix. In contrast, the DPWA aggregates exhibited weak adhesion, along with voids observed between the DPWA aggregates and the matrix. These SEM observations confirmed earlier reported mechanical and thermal characterization findings.
- This study examined the LCA for external walls insulated with air blade, and LWSs made of 50% and 65% EPS beads. The results show that the more lightweight the samples, the lower the environmental impact. It can be found that for all effects, LWS containing 65% EPS is more environmentally friendly than other insulating materials.
- The results of this study can be applied in the construction industry to produce sustainable and environmentally friendly insulation materials using raw earth incorporating EPS beads and DPW.

General conclusion and perspectives

General Conclusion

Earth-building is considered one of the oldest methods in human history. It has been used in most countries of the world, especially in ancient civilizations, on a global scale due to its cost-effectiveness and natural benefits, as well as its good thermal insulation. However, as time progressed, construction techniques rapidly evolved, giving rise to new materials like iron, cement, and concrete. Despite their advantages, these materials exhibit lower thermal insulation capabilities compared to adobe or bricks, leading to heightened energy consumption for heating and cooling requirements. Furthermore, the manufacture of these materials has also caused climate change, global warming, and environmental pollution resulting largely from gas emissions, especially carbon dioxide. In order to reduce these negative effects, we focused in this study on relying on natural thermal insulation materials, which offer superior energy efficiency, environmental sustainability, and health benefits, all while ensuring cost-effectiveness. Therefore, our work aims to determine thermal, physical, and mechanical properties, as well as mechanical behavior, related to the use of this material in buildings. Additionally, part of this study also focuses on analyzing the life cycle of the material, from the raw material extraction phase to demolition.

New domestic building materials have been developed for buildings with good thermal insulation. In this context, expanded polystyrene beads and date palm waste resulting from the process of crushing palm maintenance waste (palm part), which are abundant in Algeria, were used in the manufacture of lightweight earthen bricks stabilized with quicklime.

The incorporation of both plant and synthetic fibers and aggregates represents a relatively recent innovation in the field of civil engineering. Therefore, we commenced our research by conducting an extensive literature review on the utilization of plant and synthetic fibers and aggregates within soil matrices and their diverse applications. According to the literature, the inclusion of plant fibers adversely impacts the compressive strength of earth samples. Similarly, the effect on the compressive strength of synthetic fibers is contingent upon the material's inherent nature and the percentage incorporated. Nonetheless, the integration of synthetic or plant waste into the manufacturing of building materials has been observed to minimize heat transfer within buildings.

Moreover, our investigation revealed that the integration of expanded polystyrene beads into the soil matrix had not been previously studied. Also, most previous research related to the use of palm waste in soil was based on maintaining minimum thresholds of mechanical resistance.

The raw materials used in this study were described in chapter three. In this work, local materials were used to make earthen samples based on expanded polystyrene beads and date palm waste as follows: soil and quicklime as a chemical stabilizer, expanded polystyrene beads, and three sizes of date palm waste: DPW < 1 mm, DPW (1–5) mm, and DPW (5–10) mm and water.

In the fourth chapter, all the results and discussions were presented. In this chapter, we studied the effect of incorporating two different types of aggregates. Artificial aggregate, represented by expanded polystyrene beads, and natural aggregate, represented by date palm waste on earth stabilized with lime. The physical, mechanical, and thermal properties of the earth samples were measured by varying the EPS content from 40% to 65% by volume, as well as a life cycle analysis study of the external walls constructed using lightweight earth samples stabilized with lime and containing 50% and 65% EPS beads to evaluate their environmental impact. In addition to studying the effect of DPW content from 40% to 75% by volume for three different sizes of DPW on the physical, mechanical, and thermal properties of kightweight samples, The results can be summarized as follows :

- The lightweight earth samples containing expanded polystyrene beads exhibited a notable decrease in apparent density. In contrast, those incorporating date palm waste showed a moderate reduction, approximately half that of the lightweight earth samples with expanded polystyrene beads, compared to the reference sample.
- The study demonstrated that the addition of EPS (expanded polystyrene) beads and three varying sizes of DPW (date palm waste) notably enhanced the thermal efficiency of the raw earth. Both EPS beads and DPW aggregates exhibited a significant decrease in thermal conductivity compared to the reference samples. Notably, samples with the largest size of DPW showed the lowest thermal conductivity among the three sizes. Furthermore, as the percentage of EPS beads and the percentage and size of DPW increased, the lightweight block exhibited a decrease in both thermal effusivity and volumetric heat capacity.

- The study findings indicated a decrease in the mechanical strength of the earth samples with an increase in the proportion of EPS beads and the proportion and size of DPW. However, there was a notable enhancement in the ductility of these samples. Specifically, samples containing 40–50% EPS beads and those with 40%–45% DPW across three different sizes, along with the reference bricks, met the Turkish standards for load-bearing walls. Conversely, the remaining samples are suitable for use in wall insulation. In addition, the study indicated a significant decrease in the elastic modulus with an increase in EPS content, percentage, and size of DPW.
- This study examined the LCA for external walls insulated with air blades and LWSs made of 50% and 65% EPS beads. The results show that the more lightweight the samples, the lower the environmental impact. It can be found that, for all effects, LWS containing 65% EPS is more environmentally friendly than other insulating materials.

In conclusion, these results indicate the possibility of using lightweight samples incorporating expanded polystyrene beads and date palm waste as an interesting alternative for producing environmentally friendly samples. These samples have commendable thermal insulation capabilities, cost-effectiveness, and energy efficiency, which are much better than traditional fired bricks and other insulating materials. Given these encouraging results, there is potential to introduce the study's products into the construction market.

Perspectives

- Experimental study of surface treatment for protection of lightweight earth blocks incorporating EPS beads and DPW.
- Study of the physical, mechanical, and thermal properties of real-scale lightweight panels incorporating EPS beads and DPW.
- Modeling and simulation of the behavior of building walls built with lightweight earthen blocks and incorporating expanded polystyrene beads and date palm waste
- Study of the durability of lightweight earth samples incorporating expanded polystyrene beads and date palm waste.

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